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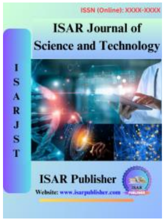

ISAR Journal of Science and Technology

Volume 3, Issue 3, 2025, Page: 58-73

Abbriviate Title- ISAR J Sci Tech

ISSN *(Online)*- 2584-2056

https://isarpublisher.com/journal/isarjst

Harnessing Phase Change Materials for Effective Cooling in Domestic Battery Storage for Renewable Energy

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Article History

Received: 17.01.2025
Accepted: 03.03.2025
Published: 27.03.2025

Abstract: Renewable energy systems coupled with the domestic battery storage are becoming more and more necessary for sustainable energy solutions. Despite this, the thermal management of lithium ion (Li ion) battery packs is a major issue due to temperature sensitivity. Thermal regulation is critical, and by doing so they can effectively optimize performance, safety, and longevity, which includes passion for burning holes through in the search of an innovative cooling strategy. This thesis attempts to examine the role phase change materials (PCMs) play in improving thermal stability of domestic battery packs. The passive cooling method offers by PCMs is based on the fact that they are able to absorb and lose heat by means of their phase transitions, and thus decrease risks of temperature fluctuations. This research focuses on thermal challenges of Li ion batteries at extreme temperatures in the off nominal temperature range resulting in increased internal resistance and reduced power output, potentially resulting in thermal run away. Active cooling systems like liquid cooling are compared with the passive PCM based solutions. Recently developed PCM integration methods, including composite materials that enhance thermal conductivity and thermal conductivity cooling, are reviewed in the study as well. Experimental studies together with computational simulations show that PCMs effectively reduces peak temperature of the battery and maintains uniform heat distribution across cells of the battery. Traditional PCMs have limitations in thermal conductivity but by incorporating such additives as expanded graphite or a metal foam the performance is considerably improved. It is also demonstrated that hybrid systems that combine PCMs with active cooling methods will prove useful for thermal regulation. It presents the opportunity for PCMs to be a viable, and energy efficient, thermal management solution for domestic battery storage. The future work could aim to optimize the PCM material properties, include the hybrid cooling strategies, and progress with the real time monitoring technologies in order to improve the battery performance and reliability in renewable energy applications.

Keywords: Phase Change Materials (PCMs), Battery Thermal Stability, Renewable Energy Storage, Passive Cooling Systems, Energy Storage Systems, Hybrid Cooling Strategies.

Cite this article:

Akeiber, H. J., (2025). Harnessing Phase Change Materials for Effective Cooling in Domestic Battery Storage for Renewable Energy. *ISAR Journal of Science and Technology*, *3*(3), 58-73.

1. Introduction

1.1. Importance of Thermal Management in Battery Systems

Thermal management foam design and operation are critical for lithium ion (Li-ion) battery performance, safety, lifetime and overall efficiency, mostly by affecting the behavior of battery systems. Li-ion batteries are prone to temperature fluctuations, and good performing batteries have protection limits, within approximately the range from 15 °C to 35 °C. Failures away from this range can have a variety of negative effects on battery functionality.

Several harmful effects occur when temperatures are below recommended level. Certainly, chemicals will not react at low temperatures, and can lower internal resistance or the ability to deliver power to the load effectively globally. Severely impacting electric vehicles as well as other technologies based on these batteries, this decreased charge-discharge capability is a potential issue because the historical performance is needed to understand the disordered LiN. Batteries can become nonfunctional, or they can sustain irreversible damage due to extreme coldness, that is when temperatures go under 0 °C or even -20 °C.

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In fact, on the opposite end of the temperature spectrum, the elevated temperatures present their own safety and performance threats. However, these degradation processes can occur at high thermal conditions in battery materials like depletion of active lithium content, leading to a decrease in the overall capacity over time. Higher temperatures also cause increasingly high internal resistance, which can greatly lower power output. If temperatures exceed 60 °C in the extreme cases the risk escalates sharply and thermal runaway could start due to exothermic reactions between the cells' components. Dangerous fires or explosions are possible from such uncontrolled chemical reactions.

Apart from avoiding extreme temperatures there is a need to ensure uniform temperature distribution in Li-ion battery packs for effective thermal management. Batteries are comprised of many individual cells that are usually subjected to different thermal environments due to the cell-to-cell heating variation and cell-to-cell cooling efficiency variation, and if the management strategies were not adequate, the heating would be uneven. Since degradation rates across an entire battery pack would be complicating and the degradation rates not stable, this inconsistency makes the cell-to-cell variation more likely due to inconsistency.

Due to these challenges, urgent need exists for advanced thermal management strategies. Such effective systems have to promote the heat dissipation while providing uniform distribution of temperature among cells of a pack to avoid the development of localized hotspots, leading to premature failure. There exist several proposed and assessed methods to achieve these objectives.

Often active cooling techniques, such as liquid cooling systems, are used but add to complexity and reliability of pumps and liquid mediums. A feasible solution using passive systems incorporating phase change materials (PCMs) is to absorb excess heat during peak demand by phase transitions and sustain operation within safe limits without requiring external energy input.

In general, thermal states need to be monitored for fault detection prior to escalation to perhaps more dangerous thermal runaway incidents. Currently, various sensing technologies, such as thermistors or thermocouples, are used to thermally measure battery surfaces; however, this is done with insufficient internal measurements, which limits the accuracy in which core temperatures can be evaluated under operational stress.

Although advancements in temperature regulation at the cellular level have been made, these improvements are limited at larger scales, especially regarding the comprehensive integration of battery pack assemblies with efficient monitoring systems for real time data analytics on thermal behaviors among different operational phases.

In conclusion, focused efforts should enhance understanding of effective temperature control strategies while expanding existing methodologies for real-time state monitoring of Li-ion batteries deployed in diverse environments, from electric vehicles navigating challenging terrains to stationary energy storage solutions supplying renewable sources to power grids. Highlighting the critical importance of effective thermal management in maximizing safety and extending the lifespan of modern energy storage technologies, [1], [2], [3], [4], and [5].

1.2. Challenges in Maintaining Optimal Operating Temperatures

Thermal management in battery packs is effective for achieving maximum efficiency, safety and lifespan, and especially lithium-ion batteries. It is well understood these systems are temperature dependent and operating outside the ideal range of 20 °C to 50 °C can cause performance degradation and an increased safety risk through accelerated aging and thermal runaway that creates a very high fire hazard.

Electrolytic reactions in batteries strongly depend on temperature. Increasing the temperature results in faster charge transfer resistance that reduces power and efficiency, whereas higher temperatures promote reaction rate increase but promote detrimental side reactions that threaten the integrity of the battery.

It is important to ensure uniform temperature across battery cells; even relatively small deviations may reduce capacity and power. Thermal inconsistencies are related to such factors as cell placement and heat dissipation methods. Modern batteries produce significant internal heat during use, which requires strong cooling solutions to avoid localized overheating that stimulates degradation and increases the safety hazards.

Thermal management becomes more complex under environmental conditions. Special designs are required so that batteries operating at extreme temperatures can maintain performance safety. Liquid cooling is a very active system solution for cooling heat in high temperature conditions, but it adds the problems of weight and maintenance to the system.

Another challenge in the implementation of thermal management states the material to choose. Phase Change Materials (PCMs) simply change phase and absorb or release latent heat during the phase changes. Current PCMs however, possess suitable change point temperatures relative to application requirements, but there is difficulty in identifying PCMs with thermal conductivity properties that also ensure thermomechanical durability through the necessary cycles while operating.

Ongoing efforts for providing optimal PCM characteristics for a wide range of charging scenarios while limiting risks of thermal runaway, which results from exothermic reactions within the cells.

Standardization issues also hinder the development thermal management system. Due to the absence of standardized protocols in the testing of cooling technologies, it becomes difficult to compare cooling technologies and to evaluate them under different operational conditions. As such, this frequently results in inefficiencies, as you need reliable predictive models for the behavior of components under different conditions to predict.

The challenge of these issues requires advanced monitoring technologies. By knowing real-time temperature distribution, manufacturers are capable of identifying potential failure issues early, and implement corrective measures before those causes of degradation affect performance.

An approach such as this will energize innovation in the markets for safe, reliable energy storage solutions needed for user experience, for participation in global sustainability initiatives and efforts to combat climate change, [2], [4], [6] and [7].

2. Review of Previous Research

2.1. Overview of Phase Change Materials (PCMs)

The Phase Change Materials (PCMs) are the phase change materials and known for their capacity to absorb and release thermal energy during the phase transition process, especially from solid to liquid, to liquid to solid conversion. This ability to store latent heat makes them attractive for thermal management applications, in particular within lithium ion batteries, where efficiently monitoring temperature is so important because of the heat they produce during charging and discharging cycles. Battery performance as well as battery longevity and safety can, however, be adversely affected by temperature fluctuations.

The major advantage of PCMs is their latent heat capacity, which enables them to dissipate excess heat without substantial change in temperature. This property is useful as it helps prevent overheating and reduce the chances of thermal runaway, which is a big issue for lithium ion batteries with propensity to hazardous reactions.

PCM composition and phase change temperature are varied; and there are common types, such as paraffin waxes and hydrated salts. High latent heat storage capacity and non-corrosive nature to all type of metals makes paraffin waxes the most favorite in its application but high thermal conductivity makes heat dissipation difficult. In order to tackle this problem, researchers are experimenting with composite PCMs using additives like expanded graphite, metal foams, or mixed stiffeners and flavourings to give them high conductivity while keeping its PCM properties.

The passive regulation of battery temperatures through integration of PCMs into Battery Thermal Management Systems (BTMSs) excludes the use of energy expensive active cooling methods such as fans and pumps. More energy efficient and simpler designs compared to traditional air or liquid cooling systems are thus obtained. Experimental and CFD studies are now showing that heat transfer rates, and especially, temperature uniformity across battery packs can be significantly improved by combining PCMs with aluminum foam or fins.

Additionally, PCMs help alleviate temperature extremes in use in varying climates for which electric vehicle performance and safety depend on. It is found through research that using heating technologies and PCM solutions would also be able to improve system overall efficiency by using internal and external heating sources.

Experimental research shows that their effectiveness over the conventional cooling systems. For example, such studies show that PCM integrated systems exhibit superior uniformity among cells, lower peak temperatures in the high rate discharge scenarios, and are hence more suitable to prolong battery life.

Then, as the term for processing unit power maximization implies, the term hybrid solutions describes the emerging solutions that combine active cooling methods with PCM technologies using liquid cold plates alongside PCM strategies to provide adaptive response to the real time condition occurring in the battery unit. However, significant practical obstacles persist notably because the necessary commercial grade materials are not readily available for application to BTMS. Current research is aimed to refine the current PCM formulations and to develop new materials showing better performance in severe operating conditions.

Beyond battery thermal management, the versatility of PCMs is much greater: for instance, PCMs have the potential to be deployed in many companies from heat-treating industry to construction materials and electronic components depending on their ability of efficient thermal conduction. Recent developments indicate a gradual progress toward adopting PCMs as an effective approach to address the problems of high energy density lithium ion batteries, [2], [8], [9], [10] and [11], and has enabled the power storage to be safer.

2.2. Effectiveness of PCMs in Thermal Regulation

They are important in temperature regulation of lithium ion battery packs as PCMs, which absorb excess heat during the charging and discharging cycles, and improve the thermal management. Such an absorption happens by means of phase transitions wherein PCMs are turned from solid to liquid, storing latent heat.

The most important PCMs' advantage is the fact that PCMs can hold the same temperature for all battery cells. It is known that integrating PCMs into thermal management systems is capable of lowering peak temperatures and guaranteeing uniform heat distribution across the neighboring cells. For instance, an active PCMs system using paraffin wax allowed the system to operate with high temperature stability preventing localized overheating, an indispensable factor for the operation integrity and security of lithium ion batteries.

It is shown in experimental studies that PCM technologies significantly reduce peak temperatures in comparison with conventional air or liquid cooling systems. For example, one study involves a liquid cooled hybrid PCM system to take advantage of its latent heat due to reduce the impact of high thermal energy release on temperatures. These systems are exceedingly good at absorbing heat during peak times, and releasing heat when idle.

Recently, composite PCMs offering improvements to thermal conductivity with preserved heat capacity needed for effective cooling have been developed by the advancement of materials science. Heat transfer rates have been improved significantly for the above composite by blending paraffin wax with conductive additives such as expanded graphite that facilitate heat transfer for cooling and disallowing hotspots to accumulate.

In addition, PCMs integration into battery systems provides logistics advantages compared to conventional active cooling methods because they are easy to incorporate into a battery system without a complex setup of many components that add weight and potential failure points. Notably, PCM based systems allow for a less complex design as there is no need for additional mechanical apparatus or energy consumption associated with active cooling schemes.

I have also modeled PCM systems in case studies of different vehicle configurations. The results of research conducted on electric scooters indicated that PCM technology decreased maximum operating working temperatures up to 17.5 degrees Celsius lower than natural convection cooling. These results show an improvement in performance and a better battery life given reduced thermal stress.

Computational fluid dynamics (CFD) simulations have demonstrated that this agreement between experiment and CFD models is consistent under normal and extreme conditions for temperature profiles within PCM integrated battery packs. Using these predictive models, we optimize the designs before embarking on the creation of physical prototypes with built-in efficient thermal management strategies from the beginning.

Although there are benefits to removing PCM, they are not without challenges, mainly (1) their lower thermal conductivities reduce the transient response times compared to active systems, especially at high discharge rates common to Performance Applications. However, surface area interactions of the PCM with the enclosing components have been improved by innovative designs with fins or other improvements enhancing overall efficiency.

In continuation, these challenges are being dynamically addressed in ongoing research, which is based on multi layered PCM structures that remain cost effective since ECC market forces of consumer expectations of range, performance metrics like range and charging efficiency also impact the cost of electric vehicles. As demand for effective energy storage solutions grows promoted by myriad of previous studies showing promising results of applying advanced PCM technologies to such applications, [1], [2], [7], [8], [9], [11], [12], [13], [14], [15], [16], [17] and [18]. Future initiatives to incorporate advanced PCM technologies into new designs as well as retrofit existing lithium ion battery frameworks may prove to be instrumental in developing next generation thermal management strategies.

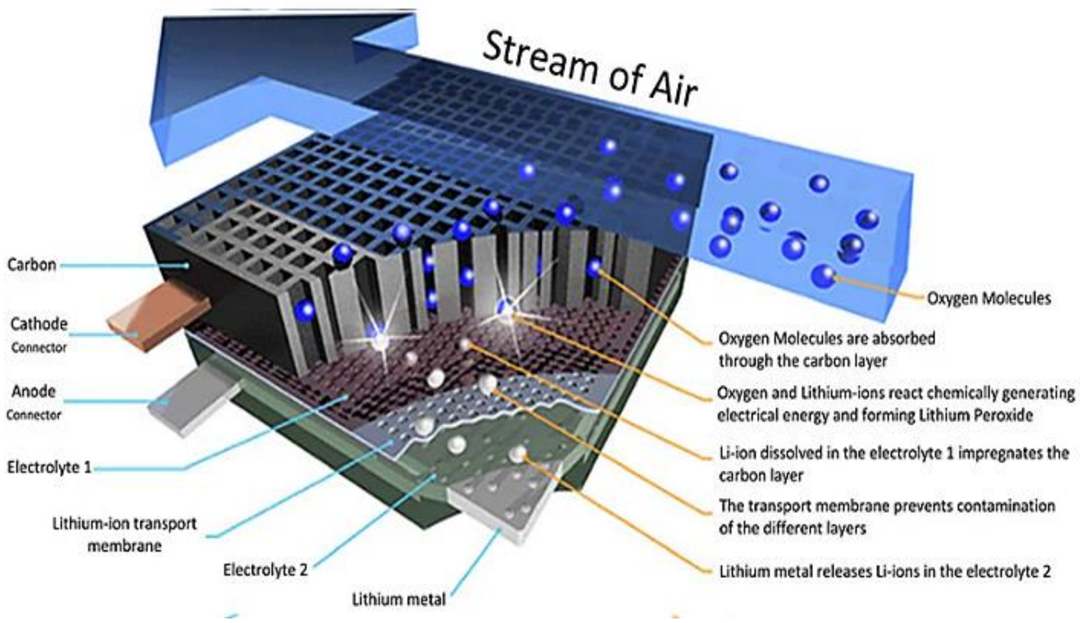


Figure 1: Overview of battery thermal management based on phase change materials, [16].

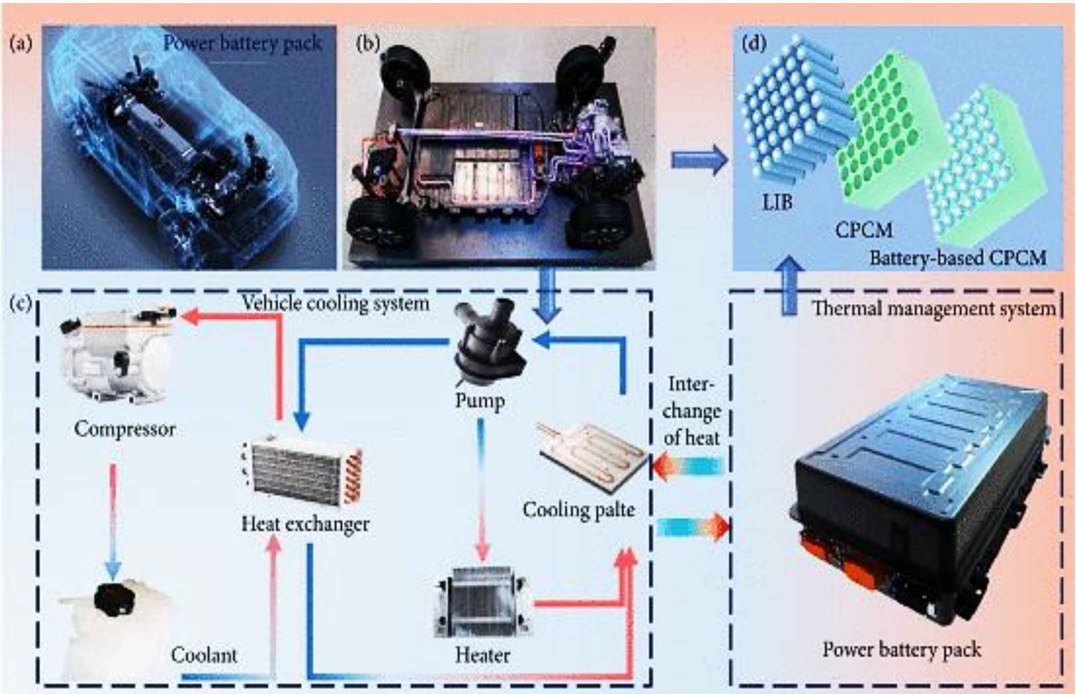


Figure 2: (a) The battery pack of EV installed in the chassis, (b) The battery pack between the front and rear axles, (c) The battery pack cooling and other dissipating heat devices in EV, (d) The CPCM as the passive cooling approach in the battery pack, [13].

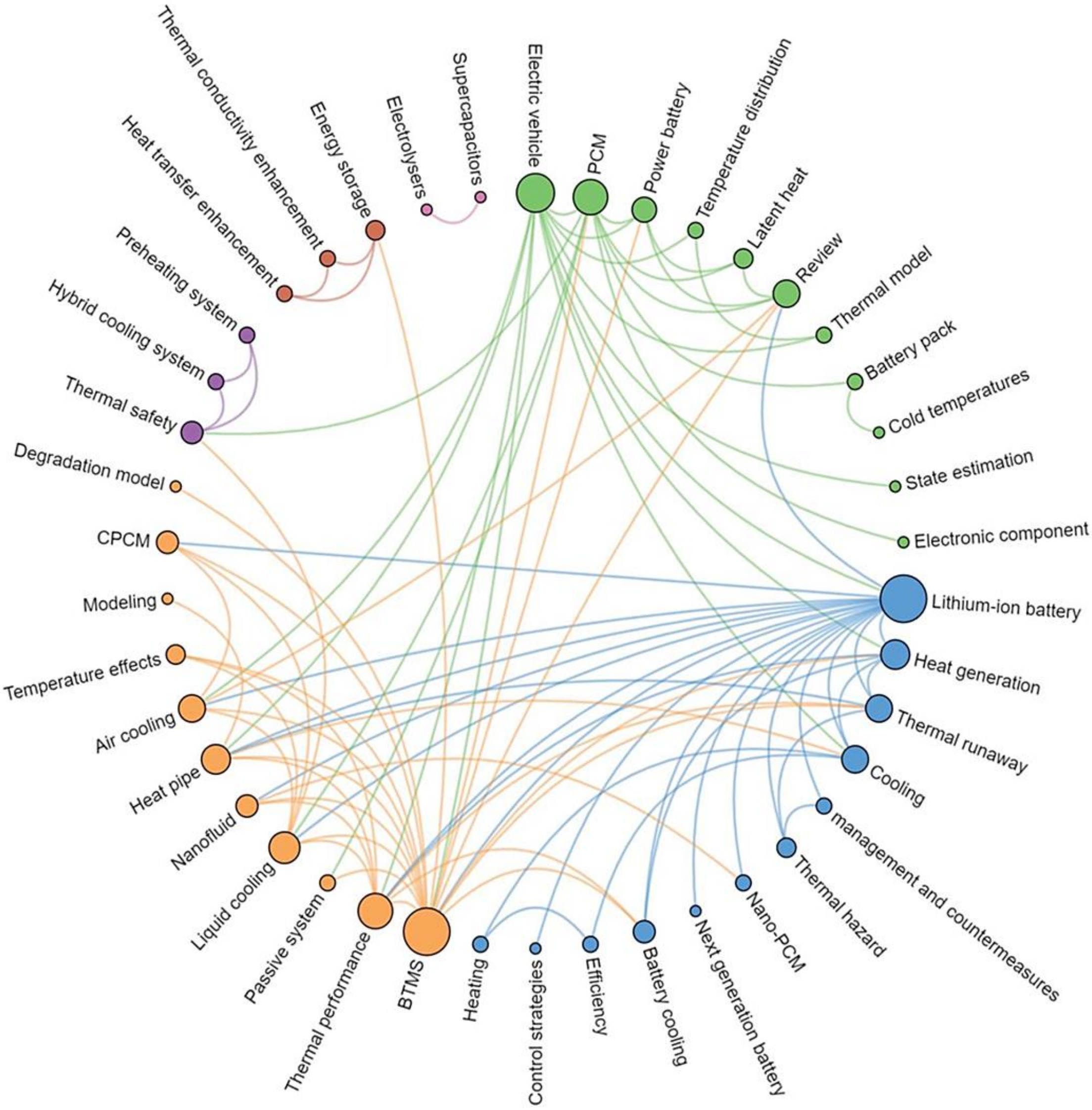


Figure 3: Keywords co-occurrence network of the review, [9].

Some important academic studies have discussed the need of battery packs to operate at optimal temperatures within the realm of thermal management. Zheng et al. conducted a preliminary investigation into a thermal management system for batteries based on a strategy arrangement of flat plate heat pipe array, showing that performance of heat transfer is important with respect to improving both battery efficiency and battery safety (Zheng et al., 2020). In a similar vein, Saw presented a novel mist cooling system for lithium ion batteries that had experimental and numerical comparative advantage to ordinary air based cooling systems (Saw et al., 2018).

Thorough different research has been made so far of the role of phase change materials (PCMs) in confronting thermal difficulties confronted by lithium-ion batteries. For example, Liu et al. provide a thorough overview of PCM applications in battery systems and provide criteria and methods to improve their properties (Liu et al., 2020). Zhao et al (2023) also studied decanoic acid based composite PCMs for use in thermal management of batteries, further strengthening the role of material characteristics in yielding reliable solutions in case of operating in different conditions.

In addition, there has been considerable interest in potential of nano-enhanced phase change materials (NePCMs). Sevugan, A. et al. (2022) stated that as NePCMs can provide substantial thermal conductivity and performance enhancements, they might address limitations of conventional PCMs. In a complementary piece of research by Olabi et al., various cooling strategies required for the development of battery thermal management systems (BTMS) and advanced lithium-ion battery (LIB) technologies were considered and such creative approaches were necessary to enhance the safety and further the longevity of lithium-ion batteries (LIB) (Olabi et al., 2022).

To enable effective control of heat in lithium ion battery packs, Chalise and his team investigated conjugate heat transfer analysis techniques that perform well at controlling heat in batteries (Chalise et al., 2018). In addition, Hasan stated that the utility of those PCMs needs to be determined by its use within a specific range of operational temperature to maximize efficiency with a minimum risk of thermal runaway incident in battery systems (Hasan et al., 2010).

These studies highlight not only the point of the need for rigorous experimental validation, but also the necessity to incorporate robust theoretical models in the development of effective thermal management systems to sustain performance under diverse operating environments as discussed in [2], [3], [10], [19], [20], [21], [22] and [23].

3. Methodology and Equations

3.1. Theoretical Framework for PCM Analysis

Utilizing the energy conservation equations that describe thermal behavior forms the theoretical basis for gaining an understanding of phase change materials (PCMs) in thermal management systems for batteries (BTMS). It addresses analytical, as well as numerical modelling techniques for predicting how both temperature and the heat capacity of battery packs change as latent heat of a PCM is absorbed or released during its phase transition.

In order to thoroughly understand PCM dynamics, it is necessary to identify such important thermophysical properties as specific heat capacity, latent heat of fusion, thermal conductivity, and phase change temperature. They are essential attributes for the evaluation of PCMs as thermal regulator for battery application. Conceptually, a PCM should have a melting point higher than ambient temperature but lower than the maximum target operating temperature of the battery system. In addition, it should have a large latent heat capacity should it be used to absorb excess thermal energy during the peak operational periods.

Energy conservation equations are formulated and from these models, analytical models begin with illustrating heat generation within the battery pack resulting from the electrochemical reactions. The equation includes these modes of heat transfer: conduction through solid material, convection with surrounding fluid, and radiative heat transfer at high temperatures. Analytical derivations usually give closed form solutions that allow quick temperature distributions to be evaluated over different geometrical configurations and material properties and without undertaking abundant computational resources. Such an approach proves to be more suitable for smoothening integration with other models describing electrochemical reactions in batteries.

When it comes to PCM based BTMS configurations, it is usually addressed using lumped capacitance model. In particular, this technique simplifies calculations assuming uniform temperature distribution through each component, which is particularly handy during early stages of design or for complex geometries that would be very challenging by means of finite element analysis. If resistances to convective heat transfer are small compared to characteristic lengths, the assumptions of the lumped model are valid.

With these calculations, numerical simulations by means such as computational fluid dynamics (CFD) supplement analytical results to assist with transient thermal behavior as a function of several operation parameters. Such simulations allow engineers to try out alternative designs for optimal placement and configuration of the PCM around batteries while still generating what we believe is a highly realistic simulation of extreme cases or unusual operating conditions.

Iterative techniques have been designed in the recent years to solve more complex conjugate heat transport problems with both the solid and fluid domains in BTMS setup using PCMs. Simultaneous resolution of conduction in solid materials are provided such as battery casings. As well as convection with circulating coolant fluids, an important consideration because of the heat production from battery load.

This theoretical framework also requires consideration of boundary conditions that are affected by external factors (such as ambient temperatures and wind flow) onto the total effectiveness of the system. Since these conditions significantly shape both their short-term thermal management capabilities and long-term durability and safety with respect to the thermal runaway phenomena commonly associated with lithium ion systems, accurate definition of these conditions is important.

In addition, if datasets collected from experimental studies or simulation results can be employed, advanced algorithms such as artificial intelligence (AI) models can be integrated for PCM performance predictive capability based on their advanced algorithms using extensive datasets from experiment or simulation results. Neuromorphic algorithms, like neural networks, can predict the outcome of such cycles in terms of output temperatures, for different cycling conditions, with reduced computational overhead for rapid iteration of many design iterations.

This comprehensive theoretical framework enables researchers and engineers to validate existing designs and to generate new methodologies for optimizing PCM effect in the batteries that can be found today, such as cylindrical cell batteries in electric vehicles and prismatic batteries in consumer electronics.

However, theoretical advances are continually refined through experimental calibration to real world performance data such that as new materials come to action or existing ones are enhanced through the use of additive manufacturing techniques or via composite material improvements in thermal conductivity without degrading the inherent performance merits of phase change behavior, [2], [11], [14], [22] and [24].

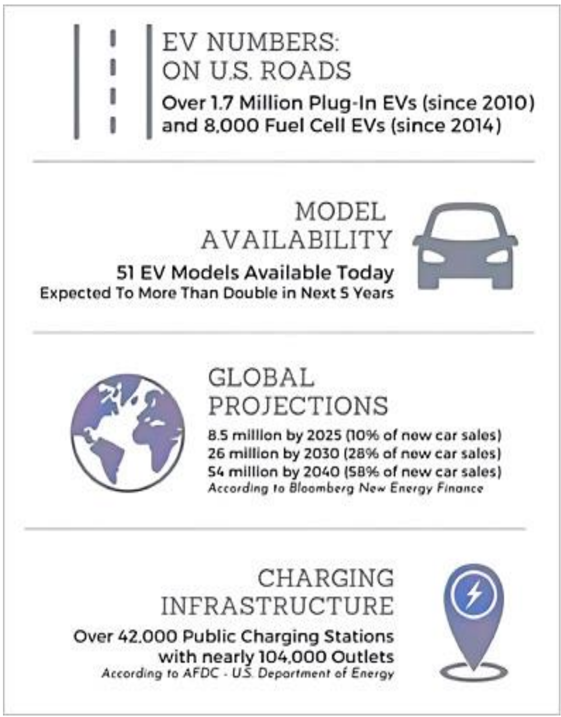


Figure 4: Statistics by Electric Drive Market Association, US, [11].

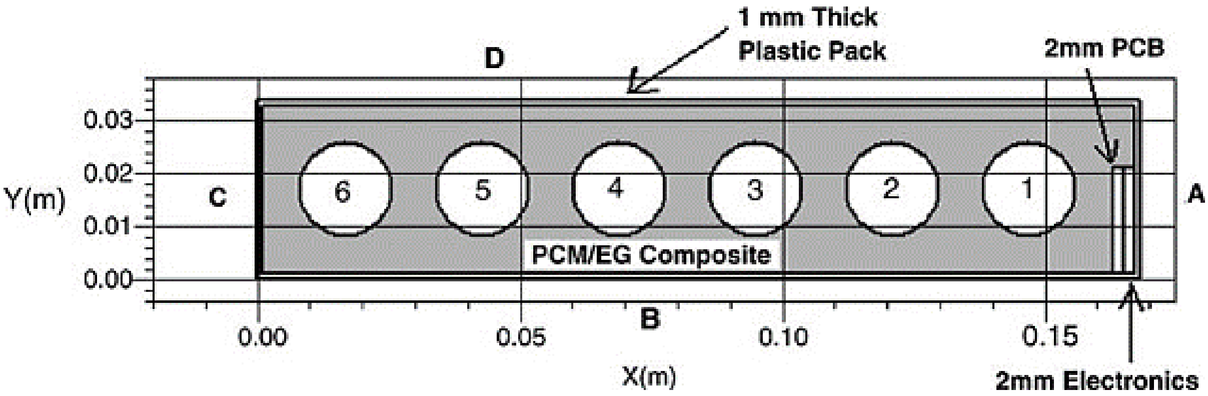


Figure 5: Schematic of battery pack used in simulations, [11].

3.2. Simulation Software Employed for Performance Evaluation

The simulation of battery thermal management systems using phase change materials (PCMs) is improved with using simulation software. Thermal management of batteries is essential to keep the product safe, efficient, and long lasting. Some such software have been developed to model complex thermal behaviours of battery cells under various conditions.

Simulating these systems is very important and MATLAB and Simulink are very useful to simulate them so engineers can create detailed models that include heat transfer like conduction, convection, and radiations. The heat absorption and release behavior of PCMs in charge dis-charge cycles is best understood with these simula-tions and engineers can then develop tailored heating or cooling solutions.

One of the main strengths of MATLAB and Simulink is their ability to conduct what-if scenarios in extreme temperature for the simulation. It gives the designer the capability to test potential failures or inefficiencies in thermal management strategies by adjusting the parameters such as ambient temperatures and PCM properties. Physica tests can be eliminated, or 'fined tuned' designs are available before the physical testing.

In addition, the tools such as Simscape Battery make the modeling of the battery systems more realistic under varying ambient conditions. Through these simulations, temperature distributions over time can be analyzed with different factors such as ambient temperatures and connection of cooling plate, to determine the hot spots that may affect performance or safety.

Thermal management systems with PCMs require the use of CFD software for their assessment. Fluid flow patterns and heat transfer efficiency are important to understand how coolants can dissipate heat from battery cells, and CFD simulations provide an understanding of the fluid flow patterns and heat transfer efficiency. The optimization of cooling channel configurations as well as heat exchanger placement is supported by visualizing the movement of the fluid.

Adding the forecasts from advanced algorithms such as neural networks to that of the traditional simulation methods improves the accuracy of predicting battery temperatures. By using machine learning approaches, quick analysis of multiple datasets from simulations gives insight into trends and correlations that suggest cooling strategies and performance metrics with low computational costs.

These methodologies complement Finite Element Analysis (FEA) as it gives insights about how structural materials affect heat flow of the components. Selecting materials with PCMs can provide optimal performance if some of this information is known.

The hardware in the loop testing is an interfacing of a simulated model with the real world applications to validate itself against physical set up. Real time data are included in the simulations to feedback actual performance metrics gained from trials into more detailed models, which could be so much more refined to the real events.

PCM selection for application requirements is optimized numerically by melting temperatures and latent heats to serve design guidelines that improve efficiency and safety in thermal management.

Analytical and numerical methods are combined in order to deal with challenges observed in closely arranged battery cells that require active cooling as well as in conjunction with passive PCM systems.

These advanced simulation tools thereby provide significant advantages over traditional experimentation for practical applications in domestic battery systems using PCMs, streamlining the development processes and significantly lowering invest resources.

By integrating various computational methods, CFD and FEA, robust projections about overall system performance are obtained and physical prototypes are constructed thereafter. Each of the presented methods provides a special understanding leading towards highly efficient battery thermal management solutions that can be used at the levels of energy required for energy storage safely and efficiently, [6], [22], [24] and [25].

Table 1: Optimizing thermal batteries using numerical modelling, simulation, and experimental setups, [6].

Thermal battery optimizing technique	Area of application
• Charging time energy fraction method • Experimental predictive model	Thermal storage for general applications
• Experimentally and theoretically • CFD	Heating, ventilation, and air-conditioning (HVAC) system
• Numerical modelling and CFD	Automotive HVAC system
• Experimental	Electric vehicles
• Crank–Nicolson numerical approach	Building
• Numerical modelling	Building application
• Experimental setup • Numerical calculations	General application
• Experimental	Cold chain transport
• Experimental analysis	Industrial application
• Experimental	Military weapons
• Laboratory scale system experiment	Domestic heating and hot water production
• Finite volume method and partial different-finite element method	General application
• Experimental	Hot water for households
• Numerical studied using ANSYS Fluent 15.0	General application
• One-domain continuum based on finite volume method	General application
• Experimental	Mechanical ventilation system
• Three-dimensional numerical model	Solar air heaters
• Numerical calculations	Solar air heaters
• Experimental setup	Solar domestic hot water
• Numerical simulation	Domestic and space heating/cooling
• Numerical modelling	Solar-concentrated heating system
• two-dimensional numerical method • Experimental	General
• Simulated numerically	Concentrated solar heating system

4. Practical Aspect

4.1. Real-World Applications of PCMs in Domestic Battery Systems

Integration of phase change materials (PCMs) into residential battery systems is a leap forward in thermal management as well as energy storage units and especially electric vehicles (EVs). Phase transitions of the PCMs can absorb and release large amounts of thermal energy, effectively stabilizing critical temperature ranges, which promotes functional areas for optimizing battery performance and lifetime.

Composite PCMs containing additives such as expanded graphite or metal foams can increase the thermal conductivity in order to enhance heat distribution in the battery pack of electric vehicles. This methodology enhances the thermal stability of lithium ion batteries reducing peak operating temperature as well as the overheating risk for increased safety.

In domestic energy storage systems, based on renewable sources, PCs are also used. By minimizing temperature fluctuations associated with ambient conditions changing, or load demands, they help render the operation at the highest temperatures possible during charging and discharging cycles. Continuing with this example, a home solar energy storage system employing PCM technology handles the excessive heat in peak sunlight and avoids cooling beyond necessary levels at night, when energy is quarried from the stored reserves.

PCMs are effective in real world applications. The results of research on autonomous underwater vehicles (AUVs) using advanced composite PCM materials for battery thermal control showed very low maximum operational temperatures compared with those of configurations with no such materials. Not only does it reflect enhanced thermal performance, but advances safety, which is of primary importance to lithium ion battery, given the risk of thermal runaway.

Furthermore, the integration of PCMs in electric mobility is also environmentally beneficial. Passive cooling using PCM integrated designs optimizes temperature regulation and therefore reduces overall energy consumption of the system, as they do not rely on active cooling systems that would consume more energy. This is particularly valuable in applications applying to the domestic arena where a constant efficiency is vital.

PCM integration with other cooling technologies such as liquid cooling or thermoelectric units are becoming increasingly optimized in terms of innovative designs. These strategies are hybridized as proposed design combine PCM with thermoelectric cooling elements to meet the variable operational conditions. This would further improve heat management and reduced dependence on environmental conditions for battery life, essential under different usage scenarios.

Developing new PCM formulations with higher heat of fusion and reduced thermal conductivity is a subject of great interest for the development of superior performance automotive batteries and domestic storage solutions. Further studies demonstrate the need for exploration of how ambient conditions affect PCM effectiveness in real applications, and thereby ammunition to manufacturers to design PCM optimally for their applications. Increasing awareness of BTMS role regulating temperatures in challenging shipping conditions, providing user safety and system integrity and meeting vehicle performance are driving the increasing adoption of modern automotive models with advanced BTMS in modern automotive models including the use of PCMs.

Overall, integration of the PCM technology is attractive by offering enhanced safety and sustainability, yet scalability and synergy with ongoing electrical storage technology development require further study, [3], [9], [26], and [27].

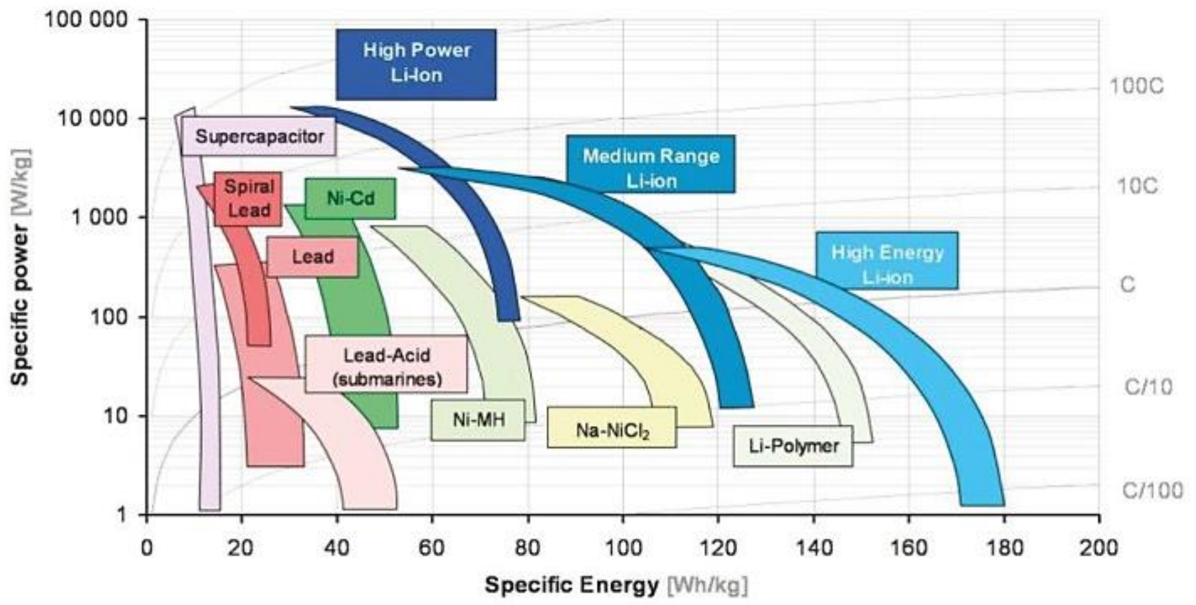


Figure 6: Ragone plot for different types of battery technologies, open access, [3].

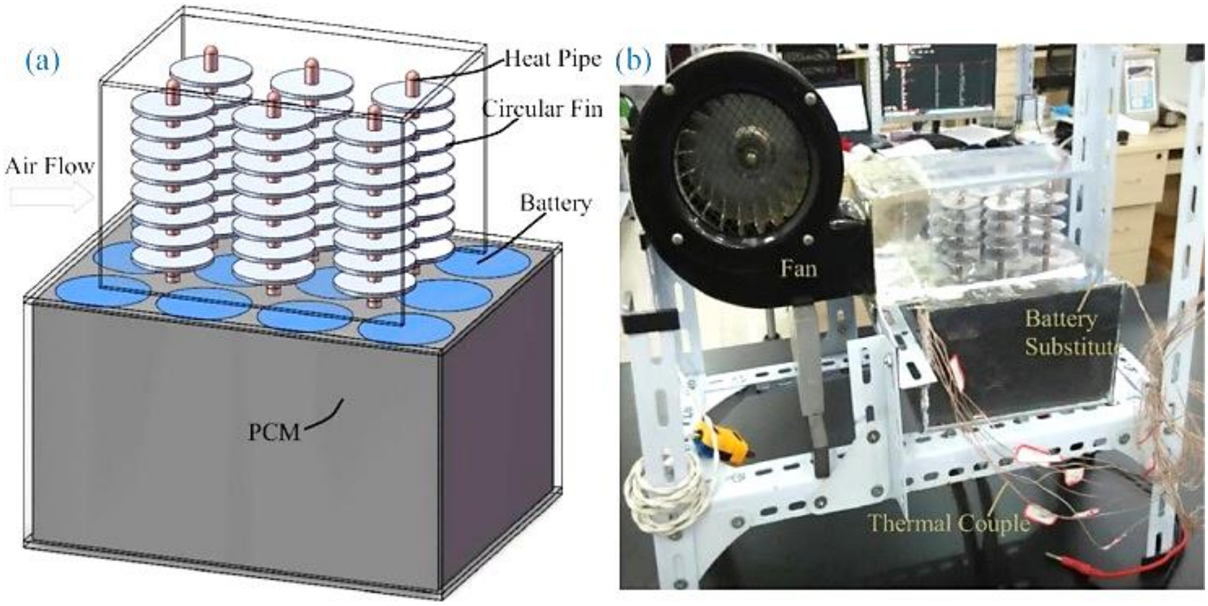


Figure 7: PCM/HP coupled BTM module (a) schematic and (b) real photograph, [3].

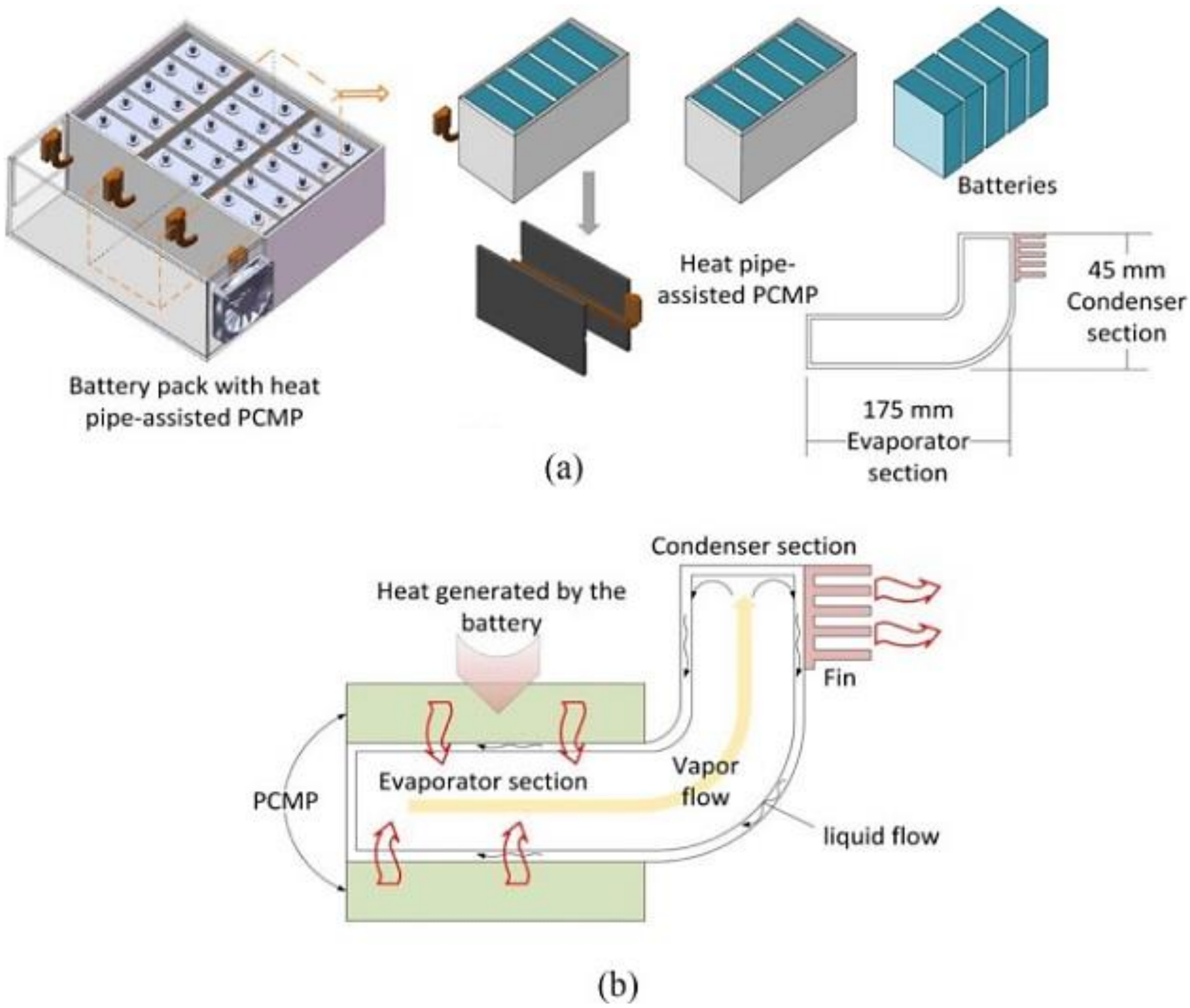
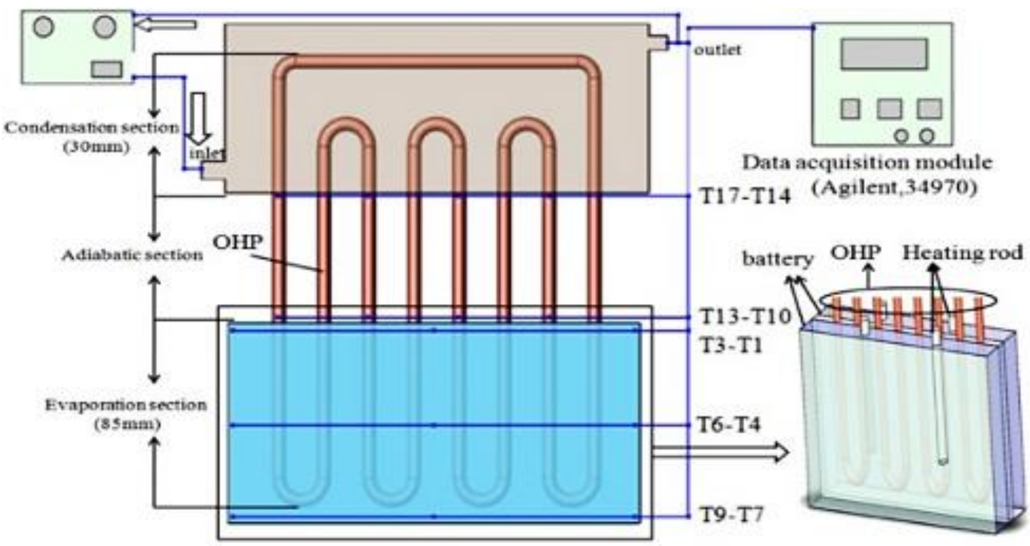


Figure 8: a) Schematic diagram of the proposed battery pack (b) principal work of integrated PCM with HP and battery cooling system, [3].

Table 2: Main features of common types of battery, [3].

Battery type	Material	Applications	Advantages	Disadvantages
Lead-acid	Sulphuric acid and lead	Car batteries, alarm systems, and emergency illumination	good capacity life, elevated voltage per cell, Outstanding results at room temperature Cheap	Brief life span. Hefty in proportion. High discharge depth. Low energy density
Lithium-Ion (Li-Ion)	Carbon anode, copper, and aluminium	Mobile phones, digital cameras, laptops, electric cars, and computers.	More specific energy. Density of energy and power. Long life. No memory impact. Self-exhaustion. Lightweight. Good effectiveness.	A thermal management system is necessary. More costly. Protection against overcharging and undercharging is necessary.
Rechargeable Alkaline	Potassium hydroxide, zinc, and manganese dioxide	The same applications as regular alkaline and carbon-zinc batteries.	Exist in different sizes. Perfect for many different uses. Non-toxic substances. No memory impact. Increase the size capacity.	Expensive to generate electricity. Possess a brief lifespan.
Nickel-Cadmium (NiCd)	Potassium hydroxide, nickel, and cadmium	Cordless phones, power tools, and professional radios	Higher specific energy with no depreciation after deep charging or discharging.	Expensive. Low energy specificity. Fixing the problem.
Nickel Metal Hydride (NiMH)	Potassium hydroxide and nickel	Cordless phones, professional radios, electric cars, and power tools	Extended cycle life. More specific energy. Wide variety of temperatures. Operate safely.	Expensive. Memory impact. Increased outflow of self.



(a)

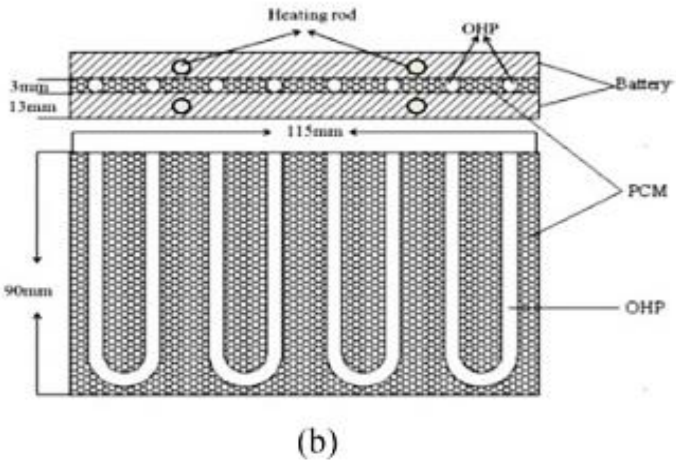


Figure 9: Battery cooling system (a) based on oscillating HP (OHP) (b) based on PCM/OHP, reproduced with permission, [5].

4.2. Case Studies Highlighting PCM Effectiveness

Phased change material (PCM) have been shown by numerous case studies to outperform other methods of temperature management in battery pack thermal conditions for electric vehicles and other battery operated technologies. For a lithium ion battery pack used in electric scooters, Khateeb et al. studied a two dimensional unsteady model that incorporated a total of 18650 batteries integrated with semi PCM's that melted in the range of 40 °C to 44 °C. Incredibly, the content mass of the PCM contributed to nearly 28.6 percent of the total battery weight, capable of receiving a fair amount of heat absorption during operation. The results indicated that with the use of PCMs, the thermal performance was enhanced significantly, and proved to be up to 17.5 °C lower than natural convection cooling in the case of use without the foam or use with aluminum foam.

In another study, numerical simulations Mlls and A-Hallaj performed on a simplified lithium ion battery pack of six cells show that under such battery pack no voltage conditions, maximum temperatures can be kept below 55 ^{o}C, which complies with the standards of the battery operation. Further, Sabbah et al. found that traditional air-cooling schemes could not ensure temperatures at an acceptable phase under such high ambient temperatures as high as 40°C to 45°C, while the PCM cooling served to control the battery temperature below critical and continued to discharge at tolerable rates.

The application investigated by Rahmani et al. an interesting one, which studied the interactions between the thermoelectric cooling and the PCM with respect to the thermal behavior of the battery, packs in general and under different operational scenarios. By placing PCMs between batteries, they found that temperatures in the pack could be stabilized maximally and secondly that temperature gradients across the pack can be minimized during operation, which is an important advantage to maintain constant thermal conditions that are important to prolong battery life.

Zhao et al.'s study on the use of composite materials consisting of anisotropic expanded graphite coupled with paraffin based PCMs is another significant example being used towards AUV applications. The results indicate impressive reduction in the maximum temperatures (nearly 29%) as well as substantial reductions in temperature differentials within the AUV's battery module during high discharge rates.

More information from Liu et al. gave a broad picture of PCM applications beyond mobile devices into larger thermal storage applications. This comprehensive analysis showed that by integrating high conductivities fillers like expanded graphite or metal foams in PCM matrices, the overall heat dissipation is still better and at the same time will not have the extra energy expense from active cooling methods.

Thaler et al. took a particularly innovative approach to solving the problem of integrated temperature management of lithium-ion batteries, which they designed additive manufacturing techniques that integrated PCMs specifically designed for lithium-ion batteries within an energy effective framework. It supports their idea that latent heat storage materials can be used to help regulate cell temperatures in a way that does not rely on external power sources that heating and cooling systems in most microscopes require.

Additionally, Aswin Sevugan's research showed the benefit of combining liquid cold plate with PCM setups maintaining their desired operational temperatures even under extreme loading conditions, typical to the electric vehicle applications.

Jointly, these diverse case studies and experimental validations from several different research teams show it is the phase change materials that facilitate the improvement of battery pack thermal regulation in several domains. To improve performance measures such as the limiting temperature of use, and importantly reduce risk by reducing overheating and thermal runaway incidents risks, [7], [14], [16], [18] [28] and [29].

5. Results and Discussion

5.1. Comparison of Theoretical Predictions with Practical Outcomes

In recent years, there has been a great deal of interest in using phase change materials (PCMs) for integrating them into battery thermal management system (BTMS) to improve heat control and battery efficiency. According to theoretical assessments, thermal fluctuations can be mitigated through charging and discharging of excess heat using PCMs. Nevertheless, standard assumptions are usually brought to bear on practical applications that then often turn out to be riddled with complications that defeat the underlying assumptions.

Theories predict different results than experiment. Theoretically, there could be uniform PCM integration on battery cells, which will simulate uniform temperature distribution across battery cells but in reality, true tests often, reveal heats or hotter spots in battery cells that the theoretical models did not foresee. These discrepancies can arise from the difference of material properties like thermal conductivity and specific heat capacity that behave differently under operating environment compared to the control environment.

Battery pack design and configuration have great impact on performance metrics. However, practical implementations can be different, as practical implementations are limited by constraints from manufacturing. Theoretical analyses can present better heat transfer by designing an optimal layout. Studies reveal that very much PCM layers thickness and structure has a major influence on thermal recuperation adequacy. An example of such complexities is an empirical study in which single layer and double layer PCM setups around prismatic batteries were compared and found to have lower temperatures when the high discharge rates, yet the theoretical expectations do not follow this pattern.

However, efficiency of PCMs is made more difficult by thermal conductivity limitations prevalent in many of them at peak loading or through rapid cycling. Modifications like embedding conductive nanoparticles can enhance them as simulated, but these cannot be implemented efficiently and in scale for practical implementation in the real world. Recent research studies have demonstrated that the nano-enhanced phase change materials (NePCMs) improve the thermal management to achieve lower maximum temperatures conditions; however there is not as consistent improvement as the thermal conditions are not controlled.

Furthermore, battery thermal behavior is also strongly influenced by environmental conditions. It is known that ambient temperature fluctuations can negatively influence performance if not factored into the design. Given that, integration of PCM technology needs to account for external factors, which are seldom considered in analytical frameworks.

Predicting PCM integrated BTMS behavior under various loads and environmental conditions requires numerical modeling, which, on the other hand, must be validated experimentally. Experiment results for temperature distributions in operating battery modules also frequently show the gaps for theoretical models, like unexpected temperature divergences between the cells, that promote degradation and reduce service life.

Despite the long-standing prediction of theory, there has been little reconciliation with practice until recently with the development of hybrid cooling methods. The combination of passive systems like PCMs is used together with active solutions like liquid cooling to extend thermal dynamics control in battery packs. While these hybrid approaches add complexity to model, they will provide better reliability to the PCM system than conventional PCM system.

Additional research further stresses the fact that there is a need for standardized testing approaches and performance metrics that are commonly applicable to a variety of battery technologies. Such standardization would allow more reliable comparison of the predicted behavior and the concrete implementation. Besides, PCM theoretically offers impressive thermal management improvements, [19], [28], [13], [9], [12], [4], yet, their practical application indicates complex coupled effects dependent on PCM characteristics and the environment, [4], [6], [9], [14] and [28].

5.2. Implications for Future Research and Development

The introduction of this review intends to paint a picture on the trajectory of research and development in thermal management for battery pack by providing few avenues promising to detour the existing quagmire, complementing the efficiency and safety of phase change materials (PCMs) in the battery thermal management systems (BTMS). The investigation of advanced composite is an important area of interest, in particular nano enhanced PCMs (NePCMs) that can make a major contribution to the enhancement in thermal conductivity. However, Traditional PCMs have limitations on thermal conductivity as well as limited performance under long-term use, especially in the presence of other conductive agents (e.g. nanoparticles) can be compensated. Better heat dissipation rates are not only possible, but also cooler batteries may last longer in a wide range of environments.

Further research should also be done refining the layout and integration of these materials within battery architectures in order to fully realize their usefulness. Such as, we may find optimal ways of utilizing multilayer PCM configurations' latent heat storage capability while reducing the risks of thermal runaway incidents. Increasing the degree of PCM structural deployment (for example using an aluminum foam or a better-designed fin) may provide more uniform temperature distribution in the battery pack that improves the overall operational reliability of the battery pack.

BTMS design includes another important area for future exploration of incorporation of innovative algorithms and artificial intelligence. Using machine-learning techniques, real time monitoring and prediction can serve as dynamic changes in the cooling strategy dependent on the temperature changes and charging to discharge behaviors. This technological integration could lead to great improvement in the way PCMS manage thermal loads during high demand like when you fast charge or discharge heavily.

In addition, delayed cooling could provide a novel means to control temperature variations in the cycle over an extended charge-discharge cycle. By examining different operational timelines for phase change materials, one can design balancing systems by which performance demands are met, and energy consumption considered, a necessary consideration for electric vehicle applications where range anxiety remains a big issue.

Additionally, the development of ways to consider the impact of vibrations on PCM performance also has a very interesting inquiry outlook. Vibrations experienced during vehicle operation could improve thermal transfer in PCM matrices through dispersion of the particles. A dual benefit from exploring optimal vibration frequencies that improve heat dissipation without affecting battery integrity is that it improves system efficiency and in turn makes the system safer.

While future investigations of PCM safety profiles should focus on the additional issue of chemical flammability and extreme condition reactions, they should not ignore the need for thorough evaluations of PCM safety in the first place. Innovative materials will need to be flame retardant so that flame retardant composites can be developed to ensure that innovative materials do not introduce new hazards in the battery operations.

Hybrid cooling methods that combine the use of passive systems like PCMs with active components may lead to synergistic benefits of optimally combining performance efficiencies and safety parameters. As energy density requirements increase in the electric vehicle applications, it is necessary to explore ways to maintain the performance without a significant increase in weight or complexity by these integrated approaches.

The last is to take the research and expand it to low temperature performance as electric vehicles come into play in markets with colder climes all over the globe. Understanding about PCM behavior in diverse ambient conditions provides a platform to develop the innovations with particular focus on those environments where traditional cooling are not efficient.

The future of research in thermal management systems for battery packs is wide open in many respects and thus brimming with potential breakthroughs to more effectively incorporate energy storage solutions for future vehicles such as [2], [9], [10] and [31].

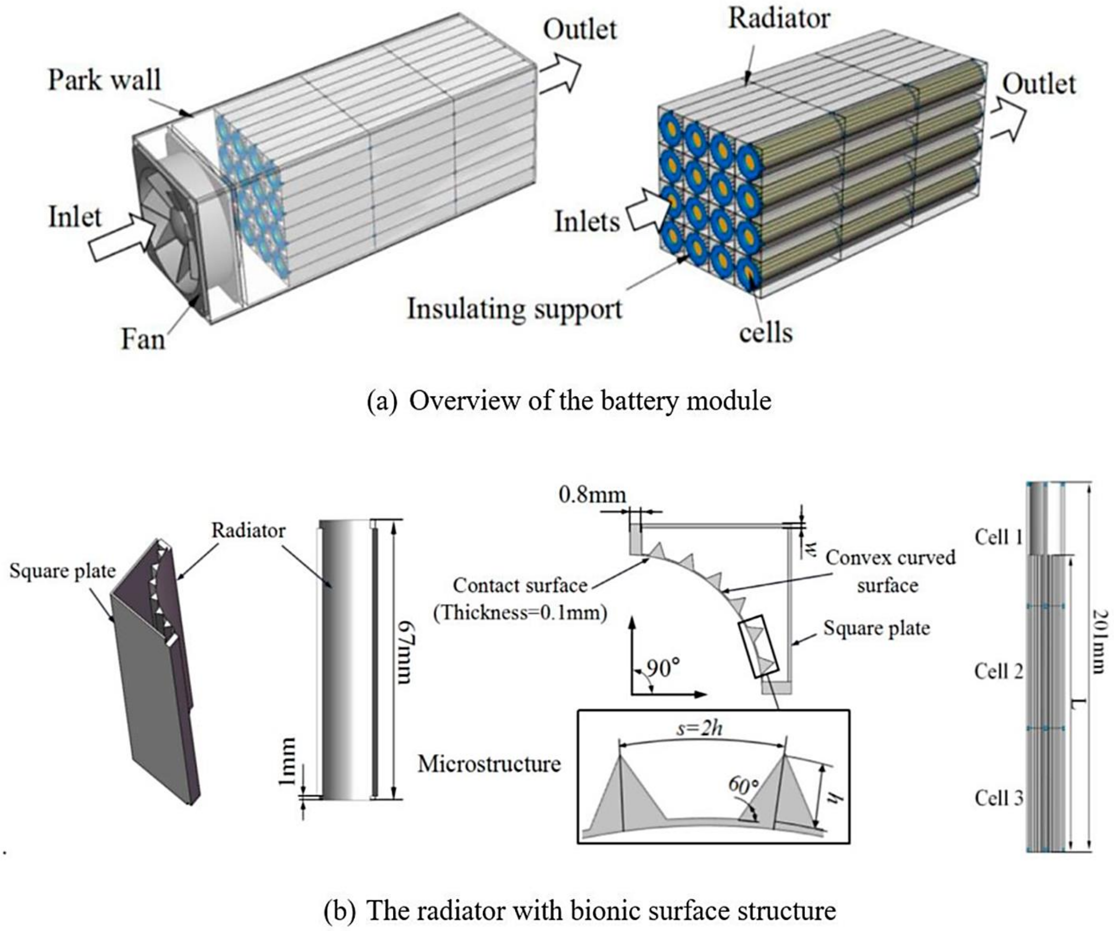


Figure 10: Scheme of the air-cooled battery management module with a bionic surface structure, [4].

Figure 11: Comparison between cooling strategies, [4].

	Advantages	Disadvantages
Air cooling	• Low cost • Simple structure • High reliability • Easy maintenance	• Low efficiency • Low cooling capacity • Noise (when using fan)
Liquid cooling	• Better efficiency • Higher cooling capacity • Flexibility in Design • Controllability • Reduced Noise (compared to air cooling)	• Complex structure • Leakage problem • Need a large space • Heavyweight
PCM cooling	• Low cost • Providing temperature uniformity • High efficiency • Simple Structure	• Leakage problem • Low thermal conductivity • Heavyweight • Flammability

6. Conclusions

It is important to point out that effective thermal management in battery packs is imperative, and of course, this can be especially vital for lithium ion batteries. Thermal management systems (TMS) for batteries in electric and hybrid vehicles are required to be robust or they will negatively influence the life of the battery, its efficiency, and the vehicle and passengers' safety. Having a battery unfolds potential for temperature control; however, the technologies behind batteries are still maturing; phase change materials (PCMs) are a promising option that are being developed to continue to provide temperature control. Using their phase transitions, PCMs have the ability of absorbing and releasing thermal energy during these transitions to maintain optimal operating temperatures without exploits or thermal runaway.

Numerous researches testified of the effectiveness of PCMs against traditional cooling methods such as forced air convection (forced convection) or cooling with liquid (liquid cooling). Furthermore, these materials do not only improve thermal uniformity of individual battery cells, but can also enhance overall energy efficiency through reducing temperature fluctuations during the charging and discharging cycles. Nevertheless, there remain serious issues in regard to thermal conductivity for certain PCMs and this can limit their use under high power demands.

The last case studies show that facility of designs with layered PCM structures can reduce weight and make a system easier to be used while also increasing the temperature management. These architectural strategies allow for more explicit control of the heat transfer rates and implement at the system level tailored solutions to the operating conditions encountered by electric vehicles. Furthermore, the use of thermally conductive fillers in PCM matrices enhances the latter's heat dissipation ability making these systems more relevant in the real world.

It is this authors' opinion that future research should focus on a number of key properties to fully exploit the advantages of PCMs in battery thermal management systems. Such studies on the stability of different PCM configurations under different climatic conditions are urgently needed particularly in view of the use of electric vehicle, as the batteries in such vehicles encounter unique problems such as capacity loss and depleted discharge performance in colder climates. Secondly, such hybrid systems may enhance the integration of PCMs with liquid or air based cooling methods by optimizing the integration of PCMs with such techniques.

This is especially true in the context where battery designs are evolving and becoming more complex. This involves formulation PCM with new materials that comply with stringent standards of safety while having high latent heat storage capacity. Furthermore, computational modeling has begun to contribute to prediction of how any given TMS configuration affects metrics of performance within a variety of operational scenarios.

Ultimately, to achieve success with advanced thermal management strategies, batteries will not only be improved in performance but will also address potential vehicle safety issues that come from the hazardous nature of overheating incidents with lithium-ion technology. The advances of this field toward more electrified transportation mode will require a thorough understanding and advancement of this field as we approach its sector oriented more toward electrified transportation, with the emergence of technological advancements.

However, despite such progress with respect to the application of PCMs within battery TMS frames, further research is required to address current limitations and new opportunities for improving both system functionality and safety. These challenges can be addressed so that lithium ion batteries continue to be a reliable power source for future mobility solutions, [4], [9], [11], [14], [19] and [31].

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