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Enhancing Car Battery Energy Efficiency with Phase Change Material Nanocomposites: A Concise Review

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ABSTRACT

This article investigates the utilization of thermal management systems for electric car applications and their optimization through the incorporation of phase change materials (PCMs) and nanoparticles (NPs). In recent years, with the expansion of the automobile sector and the introduction of electric vehicles (EVs) into the market, new challenges have emerged. One critical challenge is managing heat in lithium batteries, as the performance of these batteries can deteriorate significantly outside the normal temperature range. Consequently, this research delves into the reasons favoring passive thermal management systems over active ones in the electric vehicle industry. Additionally, it elucidates the motivations behind opting for active thermal management systems and explores research on various types of phase change materials (PCMs) utilized in this domain, along with the impact of nanoparticle additives. The objective is to comprehensively understand why researchers employ different types of phase change materials (PCMs) in this field and how these materials can influence battery cooling, including factors such as the thermal conductivity of PCMs. It also scrutinizes which materials and simulations have been proposed for these systems and assesses their potential applicability to other vehicle components, as several components of electric vehicles that remain unexamined in the literature become increasingly apparent. In conclusion, the proposal is considering the use of phase change materials in other automobile components.

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1. INTRODUCTION

In the past decades, there has been a dramatic boost in global greenhouse gas (GHG) emissions, resulting in various environmental issues, such as air pollution. Various countries have begun phasing out or banning conventional vehicles (internal combustion types) due to the increasingly poor air quality in major cities worldwide. An alternative to traditional gasoline engines is to produce and use hybrid electric vehicles (HEVs) or fully electric vehicles (EVs). Lithium-ion batteries (LIBs) serve as the power source for HEVs and EVs. Regarding the impact on GHG emissions, EVs are the best choice since they produce no emissions. In everyday usage, LIBs can also experience an increase in temperature. This is a normal part of the charging and discharging process; At the same time, a slight increase in temperature is average and not a cause for concern; it is essential to monitor the temperature of a LIB to ensure it does not become boiling. This is because charging and discharging a LIB involves a chemical reaction that converts electrical energy into chemical energy and vice versa. As chemical reactions occur within the battery, heat is generated as a byproduct.

When a LIB is charging, the lithium ions move from the negative electrode to the positive electrode, releasing electrons and creating a flow of electrical current. This process is called the charging reaction; it creates heat as a byproduct. Additionally, as the battery charges and discharges, other internal resistance and inefficiencies can cause heat (Arambarri et al., 2019).

In order to protect the battery chemical matrix from damage or even harmful runaway reactions, the generated heat during a discharge (or charge) must be adequately dissipated to the surrounding environment (Goli et al., 2014). Thermal management systems are typically used in sensitive and advanced applications like EV systems to dissipate the generated heat. An optimal thermal management system should maintain the battery in a predefined temperature range (Kenisarin & Mahkamov, 2016).

Li-ion batteries are used widely in EVs because they have heightened specific energy, high capacity, and lower self-discharge. The development of this technology still needs to be improved by some issues, such as uncontrolled and hazardous reactions caused by thermal instability (Feng, Ouyang, et al., 2018). The leading cause of thermal runaway occurs when batteries are charged or discharged without suitable heat removal (Feng, Xu, et al., 2018). However, one of the major limitations of electric vehicles is their limited range, which can make long-distance trips challenging. This is because electric

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vehicle batteries require frequent recharging, and there are still relatively few charging stations available in many areas. One of the main concerns with using traditional coolants in electric vehicle batteries is the risk of leakage. If a coolant leak occurs, it can damage the battery cells and reduce their lifespan. In addition, coolant leaks can pose a safety hazard, as they can lead to the formation of flammable gases (Guo & Jiang, 2021). According to Pesaran *et al*. (Robinson et al., 2014), LIBs should perform between 15°C and 35°C, and the temperature differential between battery modules should not surpass 5°C. Lithium batteries undergo electrochemical reactions that involve exothermic phenomena and temperature changes (Q. Li et al., 2019). If the generated battery heat does not remove, their performance and calendar life will decrease power loss and capacity fading are two main symptoms of battery aging power degradation is induced by the growth of inner resistance, which is caused by transforming reactive components within the battery into passive phases (X. Li et al., 2019).

Furthermore, another critical concern is a thermal runaway, a severe issue triggered by overheated batteries. Thermal runaway occurs when excessive heat accumulates in the battery, causing the battery to release gas or even explode, resulting in serious safety concerns for vehicles and passengers (Chen et al., 2019). Thermal runaway can also occur if temperature distribution is uneven in the battery pack (Wilke et al., 2017). Any cell whose performance declines can impact the entire battery pack, and any cell whose thermal runaway causes failure can impact the whole battery pack (Ji et al., 2019). Increasing the battery's energy density and the number of batteries can be effective ways to increase the range of an electric car. However, it is important also to consider how to handle the temperature increase in the battery pack. To maintain temperature uniformity between cells, a BTMS must control the temperature within an acceptable range range (Madani et al., 2017; Zichen & Changqing, 2021).

To oversee the stamped heat and temperature diffusion within the cells of an EV, a BTMS has become increasingly important. Batteries are commonly equipped with thermal management systems (TMS) such as liquid cooling systems, forced air, heat pipe-assisted cooling systems, thermoelectric cooler (TEC) based systems, and phase change material (PCM) implanted cooling systems (Lyu et al., 2021).

The temperature of the battery pack in EVs and HEVs. The primary function of a battery thermal management system is to maintain the battery pack temperature within optimal limits to extend the battery's life. It can do this using passive or active cooling methods and hybridizing them. BTMS also uses advanced algorithms to enhance the cooling system's efficiency and prolong the battery pack's life. Some BTMS also allows monitoring and controlling the battery pack's temperature remotely through a smartphone app or a web-based interface. Battery's specifications. It is important to note that the selection of BTMS depends on the vehicle's requirements and the battery's specifications (Hamut et al., 2016; Hekmat et al., 2022).

Passive BTMS relies on natural airflow to cool the battery pack. This type of system typically uses a combination of insulation, vents, and heat dissipation materials to control the battery pack's temperature. Passive BTMS is typically less expensive than active systems, and They consume no energy but may be less effective in extreme temperatures (Patel & Rathod, 2020).

Active BTMS uses a cooling system, such as a liquid coolant or air conditioning, to control the battery pack's temperature. This type of system can be more effective than passive systems in extreme temperatures, but it requires energy to operate. Active BTMS can be more complex and expensive than passive systems, but they can offer more precise temperature control (Alaoui, 2018).

Hybrid cooling combines passive and active cooling methods in a BTMS. This type of system uses the strengths of both passive and active cooling methods to provide optimal temperature control for the battery pack (Kojok et al., 2016).

For example, a hybrid cooling system may use passive methods such as insulation, vents, and heat dissipation materials to stabilize the temperature of the battery pack during normal driving conditions while switching to active cooling methods such as a liquid coolant or air conditioning during extreme temperatures or high-performance driving conditions (Gado et al., 2021).

The thermal management systems for batteries, such as liquid-cooling and air-cooling, frequently result in the battery pack becoming bulky and expensive due to the need for air vents, fans, pipes, and pumps. Therefore, it is necessary to implement other thermal management strategies. During the beginning of the 2000s, an innovative approach for electric and hybrid vehicle usage was presented: PCM is a type of thermal management technology. They are considered passive thermal management because they do not require an external power source. The battery thermal model was developed to encourage the adoption of PCMs and to identify the most appropriate thermal energy management design for PCMs in Automobile use cases (Gado et al., 2021; Senturk Acar & Arslan, 2018). In addition to the presented materials, many studies have been conducted on BTMSs, and Table 1 shows some of them as the reason why passive thermal management is preferred.

Table 1: Comparison of different types of thermal management systems in terms of characteristics.

	Passive BTMS	Active BTMS
Cost	Lower cost due to the small number of components.	Featuring equipment such as pumps, fans, and sensors that can increase the cost.
Maintenance	Less maintenance required.	Due to the larger number of components, they require more maintenance.
Noise	No noise produced by passive BTMS.	They produce much noise because of their pumps and fans.
Reliability	Simpler and more reliable passive BTMS	Active BTMS systems are more complex and have more potential failure points than passive thermal management systems.
Size	Due to their simpler design and lack of additional components, passive BTMS can be smaller and more compact.	Active BTMS systems typically require more space due to the additional components they use.

Despite the extensive research that has been conducted on energy management in electric vehicles, there is still a need to gather and assess this research to identify the most effective method for incorporating nanocomposites. This article will begin by reviewing studies on phase change materials and then proceed to analyze research on PCMs combined with nanocomposites to determine if the addition of nanocomposites enhances their optimization. Additionally, by examining the findings from previous studies, we will assess whether energy management can improve the navigation efficiency of electric vehicles. Furthermore, we will investigate whether the utilization of PCMs and nano PCMs can enhance navigation and increase energy efficiency in other vehicle components, such as the cabin and air conditioning systems.

2. PHASE CHANGE MATERIALS

Three forms of thermal energy can be stored: sensible heat, chemical energy from reactions, and latent heat (LH). Among these, LH has the highest capacity for energy storage (Lei & Nolan, 2014). Thermal energy is stored in phase change materials as sensible or LH and is released during reversible processes. PCMs absorb heat energy through high-temperature increases by absorbing heat from the environment and melting. When the temperature drops below the PCM's phase change temperature, the stored heat energy is released and the PCM returns to its solid shape (Malik et al., 2016). Different phase change temperatures have been classified as organic, inorganic, and eutectic PCMs (Shahbaz et al., 2016).

Traditional thermal management systems are large, expensive, and consume extra energy for operation. They also require ample installation space. PCM-based thermal management systems (TMSs) offer advantages such as lower cost, compactness, ease of implementation, reusability, ease of handling, and minimal additional components and power requirements. Utilizing PCMs to enhance thermal energy storage systems underscores their significance as alternatives to traditional TMSs (Zhang et al., 2010).

2.1.1 Categories of phase change materials

Organic PCMs are further categorized into two distinct groups: paraffin and non-paraffin. They are favored for their availability, recyclability, non-corrosive and non-reactive nature, high stability, and low flammability. Paraffin and oleic acids are commonly used phase change materials in various industries, with paraffin being the most popular due to its derivation from carbon and hydrogen. The melting point of these materials rises as the carbon atom count in their composition increases (Ghoghaei et al., 2021; Zhou et al., 2020).

Non-organic PCMs primarily consist of salts (such as hydrates) and metals. Although inorganic materials offer higher energy storage density and thermal conductivity (K) compared to organic materials, they also present certain drawbacks, such as corrosion and significant supercooling. Their working temperature is also greater than that of organic materials (Kadoono & Ogura, 2014).

Eutectics are created by combining one or two substances, either organic or non-organic, which melt and freeze homogeneously to form a blend of distinct crystals during crystallization. Eutectics are melted and frozen without dissociation and remain uniform. This category has a higher storage density than organic materials (Singh et al., 2021).

2.1.2 Heat transfer in PCMs

In systems for heat transfer (HT), the heat capacity of a fluid is a crucial factor. The higher a fluid's heat capacity, the greater the energy it can absorb and discharge. By incorporating Phase Change Materials into the fluid, its heat absorption capacity can be increased owing to the loftier energy storage density (LH) of these materials than the fluid's specific heat. The PCMs can absorb a significant portion of the energy received by undergoing a phase change, preventing the carrier fluid's temperature from rising. This results in an increased heat capacity of the working fluid, and the energy required to increase its temperature also increases compared to the base fluid (Delgado et al., 2014; Pan et al., 2012). However, it is essential to note that to reuse the PCMs in HT, they must undergo a cooling cycle to change phases again. Otherwise, their LH will no longer be available once they have melted. On the other hand, the K of the fluid is often seen to decrease in the presence of PCMs due to the low K of the shell (polymer). To address this issue, researchers have incorporated metal foam or NPs to enhance the K of PCMs and Nano-PCMs (W. Li et al., 2019; Li et al., 2018).

2.2 Empirical investigation of the use of PCM

Hallaj *et al.* (Al Hallaj & Selman, 2000) analyzed the active cooling systems for acid-type batteries in EVs and found that thermal management can improve battery performance by 30-40% through simulation. However, this type of thermal management also poses unique design challenges, and the complexity of the mechanism can make it challenging to maintain high battery system performance.

Thermal management of battery systems can be made easier using passive cooling systems that incorporate phase change materials. As illustrated in Figure 1, the integration of PCMs with the battery functions as a heat sink, absorbing and controlling heat. For instance, when the battery discharges and produces heat, the PCMs absorb it and supply it to the battery during charging or in cold weather (Al Hallaj & Selman, 2000). The use of PCMs is an ideal choice for LIBs. They offer several advantages, with a limited melting range between 30°C and 60°C and a high melting point. These include thermal diversity, low cost, safety, and a low environmental impact. Additionally, they have a lighter weight compared to other battery components (Al Hallaj & Selman, 2000).

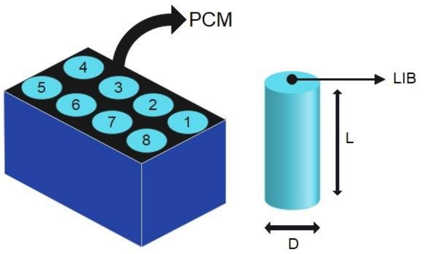

Figure 1. A schematic of the suggested EV module with eight 100 Ah cells (refer to Reference with (Al-Hallaj & Selman, 2002) permission from Elsevier).

According to Javani *et al.* (Javani, Dincer, Naterer, & Rohrauer, 2014), a PCM was applied to a Li-ion cell using CFD. Heat was generated volumetrically in the cell, and PCM was fabricated in various thicknesses: 3, 6, 9, and 12 mm. According to Figure 2, the PCM with a 12-mm thickness had the highest ΔT with a temperature decrease of 3°C. The thickness of the PCM around the cell will result in a larger radius of curvature, which will increase the weight of the battery pack. In another study, as per Javani *et al.* (Javani, Dincer, Naterer, & Yilbas, 2014), wet foam (melting point: 28–31°C) as a PCM can absorb more heat than dry foam currently used. This study involved soaking, suspending, and observing a 4-cell sub-module in n-octadecane phase change material (Javani, Dincer, Naterer, & Rohrauer, 2014; Javani, Dincer, Naterer, & Yilbas, 2014).

Based on the results, wetted foam as PCM effectively reduced the cell's temperature by 7.3°C while achieving a homogeneous temperature distribution throughout the cells. The developed model can also predict the necessary amount of PCM to absorb thermal spikes and control the temperature (Jaguemont et al., 2018).

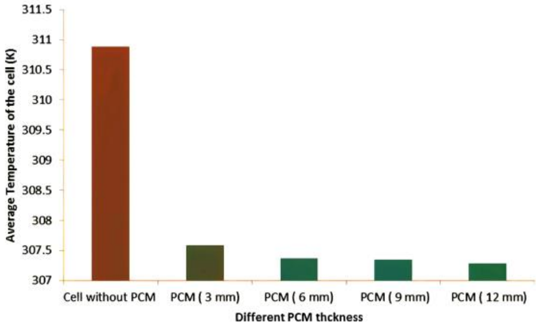

Figure 2. The moderate temperature in the cell with different PCM thicknesses (refer to Reference (Jaguemont et al., 2018) with permission from Elsevier).

Moraga (Moraga et al., 2016) presented a numerical investigation conducted on a Li-ion cell utilized in a solar vehicle. The study focused on investigating the cell's transient phase change convection-conduction phenomenon. Seven PCM arrays were examined, including capric acid (PCM 1), eicosane (PCM 2), dehydrated sodium carbonate (PCM 3), and octadecane (PCM 4). The results showed that the battery's temperature was reduced to approximately 20.9°C and 23.2°C when multiple PCMs were used in three layers and a layer of PCM was used, respectively.

A different approach was taken by Rao *et al*. (Rao et al., 2014) in their efforts to enhance the functioning of a power battery during low temperatures by minimizing the time required for cold start-up. They contrasted air heating and PCM-based thermal management solutions under severely cold conditions. The study used a 3D module containing PCM. Based on the simulation outcomes, when PCM was used for heating, the battery took 4.2 times longer to warm up from -30°C to 10°C compared to heating with air. However, the temperature gap was reduced from 9.9°C to 4.6°C fivefold, increasing the conductivity of the PCM. The study presented an effective thermal management system utilizing PCMs (Rao et al., 2014), demonstrating the suitability of PCMs for cold weather applications.

Sabbah *et al.* (Sabbah et al., 2008) experimented with evaluating the benefits of using PCMs in the battery's thermal management system. They compared passive cooling systems with active cooling systems, with one system using PCM graphite composites for cooling and heat dissipation and the other using forced airflow through fans. The results showed that PCMs were more effective at reducing heat loss in the battery and maintaining temperature differences in working conditions compared to the air cooler. The fans in the air cooling system also had the potential to wear out and become less efficient due to their heavy workload.

In recent years, significant advancements have been made in the field of PCMs, and various composite PCM composites have been developed and deployed in various applications. For example, a study by Kizilel *et al.* (Kizilel et al., 2008) investigated the use of PCMs in battery modules made of graphite composite materials. The obtained data provided an effective solution to excessive battery heat. Based on the data obtained, it was found that these composites were capable of controlling the battery's discharge temperature by up to 45%. This test diagram (Figure 3), taken from Reference (Kizilel et al., 2008), illustrates the rate of heat generation, which means that it is not only responsive at 45°C, but has a discharge rate of 2.08C, which confirms an acceptable flow rate. In addition to safely discharging the battery, it results in reduced energy loss and an extended lifespan.

Furthermore, the use of these composite materials offers improved thermal management compared to traditional cooling systems. It effectively mitigates the risk of thermal runaway, enhancing battery operational safety. Additionally, combining PCMs with graphite composites results in a highly efficient and effective cooling system, ensuring stable thermal performance and prolonging the battery's life. Consequently, the integration of PCMs into BTMSs has emerged as a promising area of research and development, with numerous potential applications across various industries.

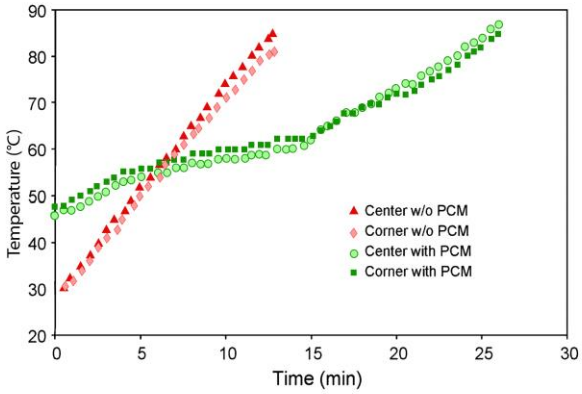

Figure 3. Temperature profile for the pack t 45°C with PCM analogized to 30°C w/o PCM (refer to Reference (Kizilel et al., 2008) with permission from Elsevier).

Additionally, the cost of producing PCMs can be relatively high, potentially leading to increased manufacturing expenses and, subsequently, higher prices for the final product. Nevertheless, the utilization of PCMs can yield substantial energy savings and enhanced performance, justifying the investment over the long term. It's essential to recognize that the suitability of PCMs depends on the particular application and its requirements. In some cases, alternative materials like traditional cooling systems or other advanced cooling technologies may prove to be more suitable and cost-effective. In summary, integrating PCMs into temperature control systems holds significant potential, but it necessitates careful consideration and analysis of the specific application and its demands (Babapoor, Karimi, & Sabbaghi, 2016; Lyu et al., 2019). For a better understanding, Table 2 has been compiled based on the reviewed research on PCMs, thus far.

Table 2: Investigation of cooling systems featuring PCM.

Authors	PCM	Density (kg/m^3)	Melting point (°C)	Thermal conductivity (W/(m.K))	Specific heat capacity (kJ/(kg.K))	Latent heat (kJ/kg)	Cell technology
Hallaj *et al.* *(*Al Hallaj & Selman, 2000*)*	Pentacosane	910 (solid) 822 (liquid)	56	0.29 (solid)	1.77	195	18650 LFP
Rao *et al. (*Rao et al., 2015*;* Rao et al., 2014*)*	Paraffin/copper foam	400	37	0.2	-	180	LFP 10Ah
Kizilel *et al.* *(*Kizilel et al., 2008*)*	Graphite composite	789	44	0.29	1.98	0.185	18650 LFP

2.3. The challenge of using PCMs based on BTMS

The most commonly utilized PCM is paraffin wax, primarily due to its high latent heat properties and non-toxicity. However, its low thermal conductivity (Ⱪ) and subpar structural durability have limited its application (Qin et al., 2019). Once melted, the low Ⱪ of PCM turns it into a nonconductor, hindering heat transfer and resulting in a sudden temperature increase. Consequently, numerous scientists have endeavored to enhance the Ⱪ of PCM by creating various composite phase change materials (CPCM) through the incorporation of expanded graphite (EXG), carbon fiber, metal foam, or other nanomaterials into a paraffin matrix.

Ling *et al.* (Ling et al., 2014) conducted empirical and computational evaluations of building thermal management systems (BTMS) performance using EXG-based PCMs. According to their studies on the phase change temperature, the optimal temperature range for phase change is 40°C to 45°C. If the composites consisting of paraffin/EXG have high density, they will exhibit high Ⱪ and latent heat in a constant volume. Increasing the density enhances the temperature increase and its uniformity. The conclusion reached by the scientists is that for this type of composite, the density should be 890 kg/m^3, with the mass of paraffin in BTMS being 75%.

Li *et al.* (Li et al., 2014) developed a sandwiched cooling system using Cu metal foam filled with PCM. The system's thermal performance was investigated with two administration cases: pure PCM cooling and air cooling. The results revealed that thermal management through natural convection (N-C) alone was insufficient to meet the safety standards of LIBs. Pure PCM was found to reduce the battery temperature and maintain it at an appropriate level due to its N-C and latent heat absorption during the melting process. The foam-paraffin composite, with its improved effective Ⱪ, led to a continuous decrease in the surface temperature of LiBs and improved temperature diffusion.

Moussa *et al.* (El Idi et al., 2021) developed an efficient building thermal management system (BTMS) for LIB cells using a composite of paraffin RT27 and aluminum foam. The objective was to maintain the cell temperature under 27°C during the charging and discharging cycles. Aluminum foam is compatible with LIB and can be useful in thermal management. The analysis of this research found that neglecting the dimensions and mass of the PCM leads to higher temperatures. Nanoparticles, including metallic, metal oxide, and carbon-based, have gained popularity for improving Ⱪ due to advancements in nanotechnology. These NP-dispersed PCMs are referred to as nano-enhanced phase change materials (NEPCM), nano-PCM, nanocomposite PCM, or CPCM. Among these, metal oxide NPs are preferred over metal NPs due to their higher resistance, affordability, and stable performance productivity (Khodadadi et al., 2013).

The utilization of nanoparticles in LIBs has introduced a promising method for thermal management. It has improved the ability to maintain the temperature of the cells within a specific range and control the rate of temperature changes during charging and discharging cycles. This has resulted in an increased heat loss rate and optimal battery performance. This article primarily focuses on addressing the thermal runaway hotspot issue, which occurs when overheating negatively impacts a battery cell. The goal is to prevent the battery pack from reaching unfavorable conditions. More comprehensive review studies are needed to examine the impact of nano-additives on the thermal management of lithium-ion batteries.

2.4. PCM selection for passive BTM

It is crucial to establish selection criteria for identifying a suitable PCM for BTMs by conducting a comprehensive review of all relevant research on battery systems incorporating PCMs (Ghoghaei et al., 2021). To make the best choice, it is essential to consider the following six points:

1. Ensure high thermal conductivity, specific heat, and latent heat (LH).
2. Verify that the product's melting point aligns with the desired operating temperature.
3. Minimize or eliminate subcooling during freezing.
4. Ensure minimal volume fluctuation during the phase transition.
5. Prioritize stability, non-toxicity, non-flammability, and non-explosiveness.
6. Confirm that it is readily available in large quantities at a low cost.

It is crucial to select an appropriate PCM for BTM systems by considering specific criteria, including high thermal conductivity (Ⱪ), high latent heat (LH) capacity, a melting point within the desired operating temperature range, minimal subcooling during freezing, minimal volume changes during phase transition, stability, non-toxicity, non-flammability, non-explosiveness, and cost-effectiveness. The ideal PCM choice may vary depending on the specific application of the BTM system. Several studies have been conducted to assess the thermal performance of various PCMs in BTMS and recommend suitable PCMs for specific applications.

PCM nanocomposites are preferred over pure PCMs due to their improved thermal and mechanical properties. The addition of nano-fillers to the PCM matrix enhances its Қ and mechanical strength, which is crucial for BTMS use (Khodadadi et al., 2013; Kibria et al., 2015). Furthermore, nanocomposites often offer higher energy storage capacity than pure PCMs, making them more efficient in controlling battery temperatures (Harikrishnan et al., 2017). Additionally, PCM nanocomposites tend to exhibit higher thermal stability and reduced thermal degradation compared to pure PCMs, making them an attractive option for BTMS applications (Jilte et al., 2020).

3. PCM NANO-COMPOSITES

PCM nanocomposites consist of a conventional PCM matrix (*e.g.*, paraffin wax) and a dispersed phase of nanoparticles (NPs). This combination enhances the material's thermal and mechanical properties, making it more efficient and durable compared to traditional PCMs. PCM nanocomposites find applications in energy storage, thermal management for electronics, building insulation, and biomedical engineering. They can regulate building temperatures, reduce heating and cooling costs, and manage heat generated by electronic components, improving device performance and lifespan.

In a study by Arasu *et al.* (Arasu et al., 2012), a physical model featuring a rectangular channel with water as the heat transfer fluid (HTF) surrounded by PCM channels was investigated. The study focused on the impact of nano-enhanced PCM (nanoPCM) in the upper half of the symmetrical model. Paraffin wax, paraffin wax with alumina (Al_2O_3), and copper oxide (CuO) were used as PCMs with varying nanostructures (1-5% by volume). Results showed that nanoPCMs exhibited higher Қ compared to pure PCMs, leading to increased heat transfer rates. Moreover, CuO nanoparticles showed a more significant increase in dynamic μ compared to Al_2O_3 nanoparticles in paraffin wax.

Auriemma and Iazzetta (Yanuar, 2016) demonstrated that embedding paraffin wax with Al_2O_3, CuO, and ZnO NPs improved heat absorption. Babapoor and Karimi (Babapoor et al., 2022) utilized a mixture of liquid-solid paraffin waxes and added metal oxide NPs (TiO_2, CuO, Al_2O_3, and graphene oxide) to create nanocomposites. Sodium Dodecyl Sulfate (SDS) was used as a surfactant to prevent NP agglomeration in the paraffin. The results indicated that the addition of NPs increased Қ and stability in the nanocomposites. The highest LH was observed in the nanocomposite with 2*wt*% of TiO_2, while the most significant Қ increase occurred in the nanocomposite with 3*wt*% of graphene. The suitable nanocomposite choice depends on the type and weight percentage of NPs used. These PCM nanocomposites have potential applications in various thermal management systems.

A study by Khodadadi and Hosseinizadeh (Khodadadi & Hosseinizadeh, 2007; Maleki & Howard, 2006) demonstrated that NPs in PCM could enhance Қ and solidification rates. Previous studies indicated that NP-dispersed PCM improved heat transfer. However, limited research has explored the use of nano-enhanced PCMs in multilayered BTMSs. The size restrictions of PCM containers in electric vehicles (EVs) make investigating their use in battery cooling systems highly relevant (Babapoor, Karimi, & Khorram, 2016).

Doping PCMs with NPs, such as metal and metal oxides, graphite, graphene, and carbon nanotubes (CNTs), is a feasible option, resulting in nano-enhanced PCMs (nePCMs). CuO and Al_2O_3 NPs, with Қ typically between 30 and 40W/m.K, have proven effective. The addition of NPs enhances Қ and improves heat transfer. It also affects LH capacity, density, and dynamic μ of PCM, necessitating an analysis of its impact on increased Қ. PCMs should be chosen based on their melting temperature, matching it with the desired operating range while maximizing Қ (Bahari et al., 2020).

Jilte *et al.* (Jilte et al., 2021) compared thermal management using three different types of PCMs. They demonstrated through simulation that adding NPs altered the thermophysical properties of PCMs, potentially impacting battery module performance. Figure 4 illustrates temperature changes in a module for various NP percentages. Within the first 100 seconds after PCM charging, NPs had a minimal impact on module temperature. Solid PCM can serve as a heat absorber. After 100 seconds of battery operation, PCM heat absorption increased with added NPs, effectively reducing cell temperature through enhanced heat absorption.

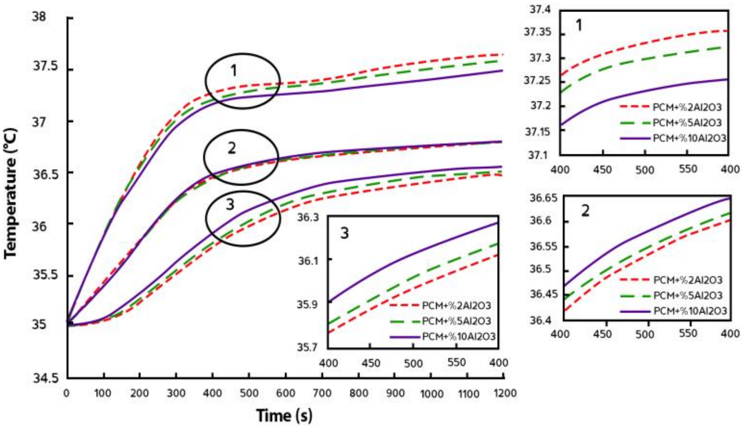

Figure 4. Cooling performance of module at different nanoparticle fractions (refer to Reference (Jilte et al., 2021) with permission from Elsevier).

Heyhat *et al.* (Heyhat et al., 2020) conducted a study to evaluate the performance of an 18,650 lithium-ion battery BTMS using PCM. They analyzed the system's efficiency by incorporating NPs with PCMs in fins and metal foams. The authors employed a local thermal non-equilibrium (LTNE) model to investigate how NEPCM melts. The data obtained from the model were validated by experimental findings, and these results were presented for two heat generation rates, 4.6 W and 9.2 W. An illustration depicting the structure of this model is presented in Figure 5. The performance of the PCM was analyzed with varying volume fractions of NPs, namely 3%, 5%, and 7%. The temperature changes in batteries containing PCM and NEPCM over time are illustrated in Figure 6. These changes indicate a slight reduction in battery temperature, highlighting the effect of the NPs. The addition of 7% NPs resulted in a 0.3 decrease in thermal conductivity at a heat generation rate of 9.2 W and 600 s. This effect was observed until the PCM was completely melted, after which it became more effective in the liquid phase. This phenomenon may be attributed to the reduction of N-C interactions resulting from the addition of NPs to the fully liquid PCM. Nevertheless, it is noteworthy that practical implementation of NEPCM presents challenges due to the difficulty in achieving uniform dispersion of NPs within the PCM.

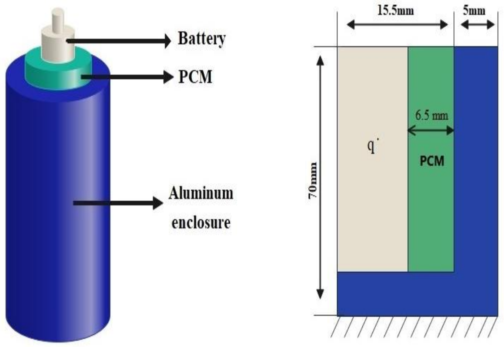

Figure 5. Schematic of a BTMS, the battery, the aluminum chamber, and the geometrical measurements and boundary conditions (refer to Reference (Heyhat et al., 2020) with permission from Elsevier).

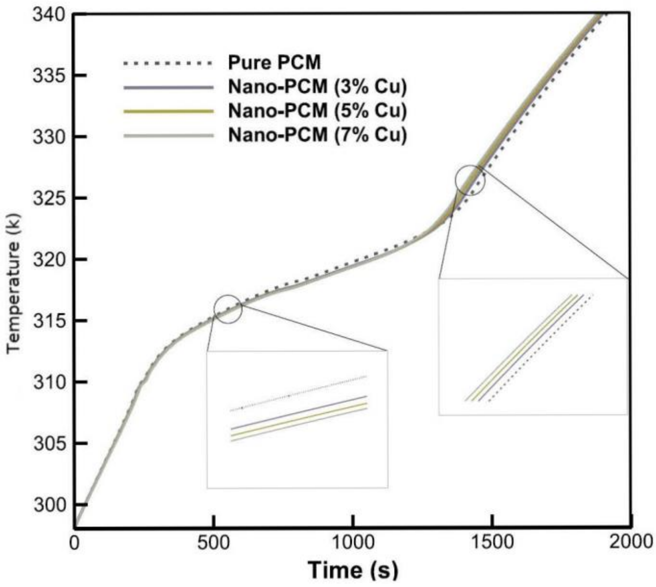

Figure 6. The effect of nanoparticle concentration on the mean battery temperature over time (refer to Reference (Heyhat et al., 2020) with permission from Elsevier).

Zou *et al.* (Zou et al., 2018) conducted an experiment related to BTMS for LIB, focusing on graphene-based carbon nanotubes (CNTs) and multi-walled carbon nanotubes. They also explored composite phase change materials (CPCMs) by combining graphene and multi-walled carbon nanotubes with paraffin wax. The process involved two steps: heating the paraffin to 70°C, mixing it with the carbon additives, and subjecting the mixture to four hours of ultrasonic vibration.

The results indicate that CPCMs based on graphene and multi-walled carbon nanotubes with different mass fraction percentages exhibit varying thermal conductivity (K) values, as depicted in Figure 7. It was observed that adding carbon additives to the PCM enhanced its K, and this enhancement became more significant as the mass fraction of carbon additives increased. Among the various combinations, the CPCM made from the mixture of graphene and multi-walled CNTs exhibited the highest K. This particular CPCM demonstrated a remarkable increase in K, with a 31.8% and

55.4% improvement compared to CPCMs based solely on graphene or multi-walled CNTs, respectively.

Furthermore, the addition of graphene and multi-walled CNTs improved the dynamic viscosity (μ) and reduced the thermal diffusivity (ℏ), resulting in a longer phase change time for the CPCM. This extended phase change time, coupled with natural convection, contributes to maintaining a consistently low temperature for the battery, preventing overheating, and enhancing the heat dissipation rate. Consequently, it is evident that thermal conductivity is closely related to the mass fraction, which explains the varying mass ratios depicted in Figure 8 for CPCMs.

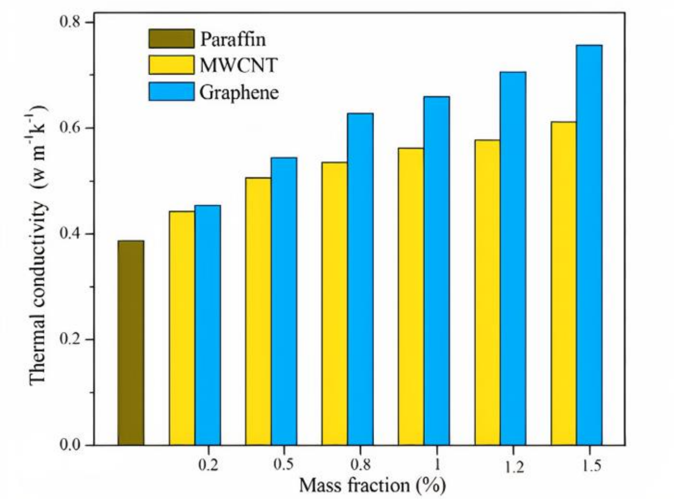

Figure 7. Thermal conductivity of graphene-based and MWCNT-based CPCMs (refer to Reference (Zou et al., 2018) with permission from Elsevier).

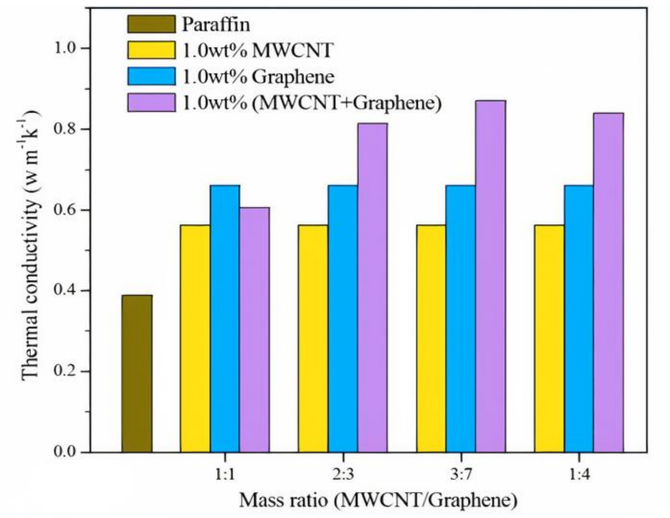

Figure 8. Thermal conductivity of CPCM with MWCNTs and graphene (refer to Reference (Zou et al., 2018) with permission from Elsevier).

Table 3. A summary of various studies on the effect of NEPCM-based BTMS on the thermal performance of the battery pack.

References	Approach	Nano additives and concentrations	PCM	Battery module details	Charging and discharging rates or $\dot{q}$	Concluding Remarks	Advantages and Disadvantages
Jilte et al. (Jilte et al., 2021)	Numerical	Al_2O_2 NPs & 2%, 5% and 10%	$Na_2(SO_4)$ $10H_2O$, and Eicosane	18,650 Li-ion cells	Discharging rate: 3C	This experiment demonstrates that the percentage of NP added can yield varying outcomes. It indicates that while a small percentage of Al_2O_2 may effectively absorb heat in one type of PCM, a higher percentage of this material might be necessary in another type of PCM to achieve the desired results.	Advantages: 1-Improved thermal management; 2- Increased energy density; 3- Longer battery life. Disadvantages: 1- Increased cost; 2- Reduced charging efficiency; 3- Limited availability.
Heyhat et al (Heyhat et al., 2020)	Computational	Cu NP, ϕ_V: 3%, 5% and 7%	n-eicosane PCM	18,650 LIBs	$\dot{q}$= 4.6 W and 9.2 W	Increasing the volume fraction (ϕ_V) of Cu NPs in PCM resulted in a slight increase in heat transfer (HT) and melting rate. Adding 7% ϕ_V Cu NPs reduced the melting time by 5% in the best-case scenario. The addition of NPs improved HT and lowered the battery temperature, although this effect was minor. Adding 7% NPs reduced the battery's average temperature (T_avg) by only 0.3 K when the heat generation rate (q̇) was 9.2 W, and the time was 600 seconds. However, this trend was observed only up to complete melting, as pure PCM performed better in the liquid phase. This could be because adding NPs to fully liquid PCM reduces natural convection.	Advantages: 1- Thermal management; 2- Energy efficiency; 3- Safety. Disadvantages: 1- Cost 2- Weight 3- Compatibility

References	Approach	Nano additives and concentrations	PCM	Battery module details	Charging and discharging rates or $\dot{q}$	Concluding Remarks	Advantages and Disadvantages
Zou et al. (Zou et al., 2018)	Experimental	MWCNTs & the ϕ_m were 0.2, 0.5, 0.8, 1, 1.2 and 1.5%	Industrial grade paraffin	LIB	NA	CPCM based on MWCNTs, graphene, and MWCNTs/graphene was produced. When graphene was added to PCM, the thermal conductivity (Ķ) improved more than when MWCNTs were used. Adding carbon additives improved Ķ while also increasing the viscosity (μ) of liquid PCM, which affects natural convection (N-C). At a total carbon additives addition rate of 1%, CPCM achieved the best heat charge/discharge effect for BTMS. In comparison to graphene-based CPCM, MWCNTs-based CPCM, and pure PCM, the results showed that CPCM with an MWCNTs/graphene mass ratio of 3/7 exhibited the best synergistic augmentation of heat transfer (HT) effect, with Ķ enhanced by 31.8%, 55.4%, and 124%, respectively.	Advantages: 1- Improved thermal stability 2- Increased energy density 3- Reduced risk of thermal runaway Disadvantages: 1- Higher cost 2- Limited availability 3- Potential environmental concerns

4. NANOFLUID-BASED BTMS

Direct liquid cooling methods are insufficient for fast charging or discharging due to the limited thermal conductivity (Ķ) of fluids such as water. To enhance the performance of the BTMS, a fluid with a higher Ķ is needed. Currently, the Ķ of typical fluids can be improved by incorporating nanoparticles (NPs).

Choi and Eastman (Choi & Eastman, 1995) initially improved heat transfer properties by incorporating NPs into a traditional fluid known as "nanofluid." NPs were chosen over larger particles due to their low likelihood of clogging or damaging channels (Das et al., 2007; Qureshi & Ashraf, 2018). NPs can be made of metal, nonmetal, or metal oxide materials, including silver (Ag), copper (Cu), copper oxide (CuO), aluminum oxide (Al_2O_3), silicon dioxide (SiO_2) NPs, and carbon nanotubes (CNTs), all of which exhibit higher Ķ compared to common fluids (Kakaç & Pramuanjaroenkij, 2009). In recent years, researchers have found experimentally and through numerical simulations that using nanofluid in BTMS is an excellent approach to maintaining constant temperature limits and ensuring battery temperature stability during fast charging and discharging.

The study by Wiriyasart *et al.* (Wiriyasart et al., 2020) explored the temperature and density fields in an EV battery cooling module using nanofluids in a corrugated mini-channel. The researchers examined the impact of the coolant's inlet and flow direction on the cooling process at different mass flow rates of water and nanofluid. Three Simulations (1, 2, and 3) were used in the study, as illustrated in Figure 9. The cooler reduces the heat released by the battery that flows through the striped channels. As a result, the temperature will be higher at the end of the cooling path, and even coolers with incompatible fluid can cause a greater temperature difference. Simulation 1 showed reduced cooling capacity at the entrance, while the cooling capacity of Simulation 3 decreased with an increase in the flow path from the entry point. Neither Simulation 1 nor Simulation 3 reached the maximum decrease in battery surface temperature. To address this issue, the researchers proposed Simulation 2, where the channels are parallel and the inlet and outlet are in opposite directions. Simulation 2 resulted in an average battery surface temperature of 38.15°C and a maximum temperature (T_max) of 51.26°C, with decreases of almost 20.34% and 27.6% compared to Simulation 1.

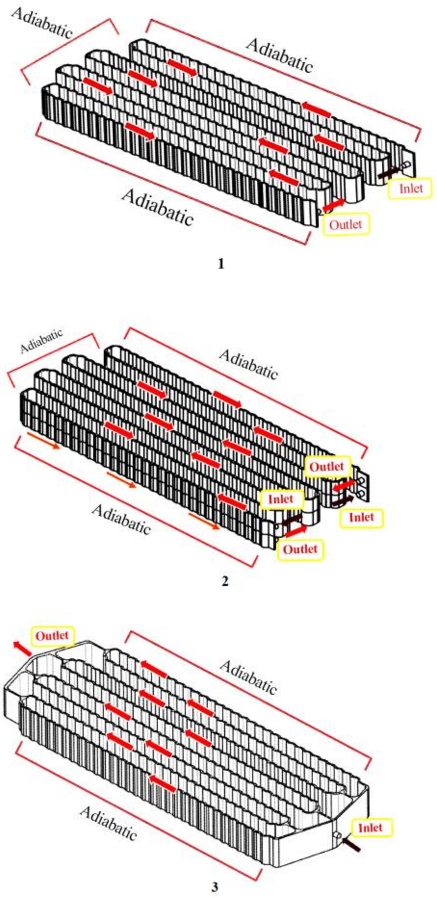

Figure 9. Computational domain of the models (Wiriyasart et al., 2020).

Mondal *et al.* (Mondal et al., 2017) analyzed the performance of six different coolers within a BTMS for a Li-ion battery. The coolants included pure water and a mixture of ethylene glycol (EG) and water with either 1% or 4% aluminum oxide (Al_2O_3) nanoparticles with an intermediate diameter below 45*nm*. The researchers also briefly evaluated copper oxide (CuO) nanoparticles, but the outcomes were similar to those of Al_2O_3. They presented the performance of another battery module consisting of 20 prismatic cells. The 20 cells were arranged in different stack configurations based on the flow arrangement (illustrated in Figure 10). In flow configuration I, the cells were stacked into two sets of ten cells each, with cooling channels in between and outside each set, resulting in three cooling channels. Flow configuration II consisted of the 20 cells partitioned into four tiers of 5 cells , each with five cooling channels.

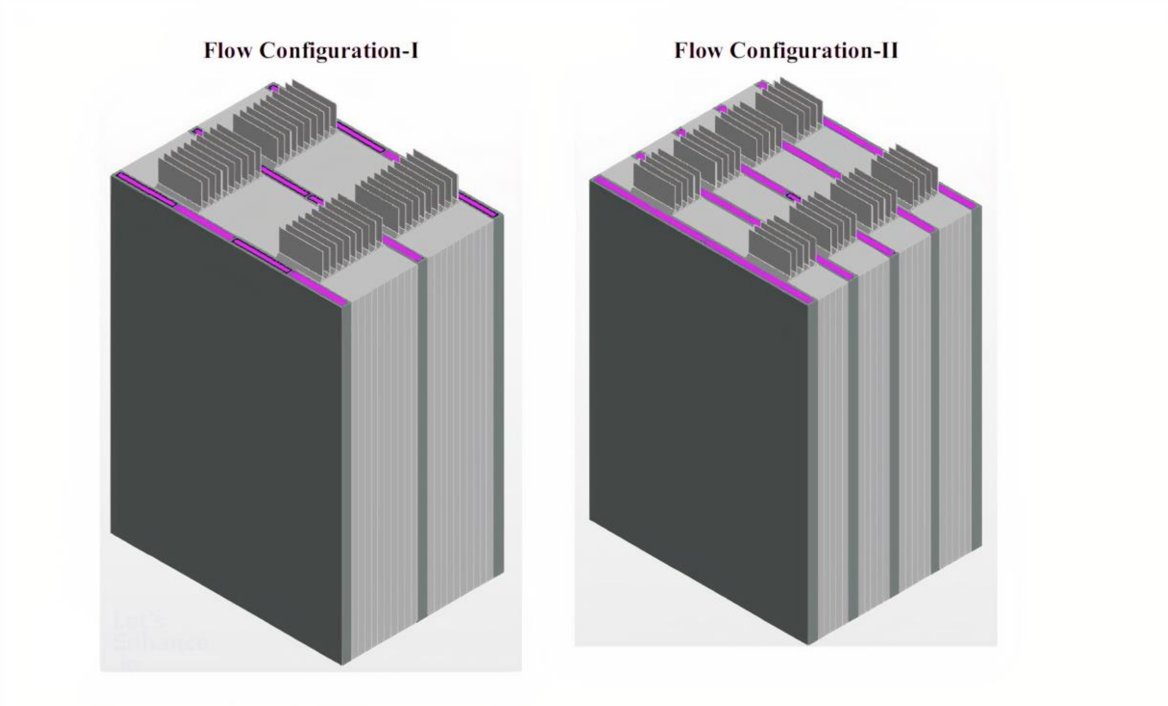

Figure 10. Schematic pieces of the battery module structures (refer to Reference (Mondal et al., 2017) with permission from Elsevier).

This study recorded T_{max} at the outlet as 5°C while the fluid temperature was 25°C. The results indicated that T_{max} could vary up to 89°C between cells, and adding nanoparticles (NPs) to cool the system did not considerably affect the module's temperature despite the increase in the value of k (Mondal et al., 2017).

Jilte *et al.* (Jilte et al., 2019) presented two approaches for organizing battery cooling systems: Liquid-filled BTMS (LcBS) and Liquid-circulated BTMS (LfBS). One advantage of this type of system is its ability to handle higher heat loads. The module comprised seven cylindrical cells (18,640 cells) in both arrangements. The LcBS immersed the cells in a container filled with liquid (as seen in Figure 11), while the LfBS placed the cells in a container that allowed fluid flow (depicted in Figure 12). The module's temperature was monitored by assigning numbers 1-7 to the cells; the first cell was located at the entrance, the fourth in the center, and the last at the exit.

The cooling effect of water and nanofluids was evaluated for both systems at discharge rates of (2C) and (4C). In general, at lower temperatures and with a cold ambient temperature, the LfBS system is more economical than the LcBS system because it does not require parts such as a heat exchanger or a pump. These devices are expected to be used in electric vehicles (EVs) operating in frigid climates. Although nanofluids can lower battery temperature in both LfBS and LcBS systems, the LcBS system demonstrates a more consistent temperature distribution. However, the heat dissipation from nanofluids was insufficient compared to essential fluids like water without additives. As a result, EVs can use liquid-cooled BTMSs with an accessible water flow system, similar to a radiator.

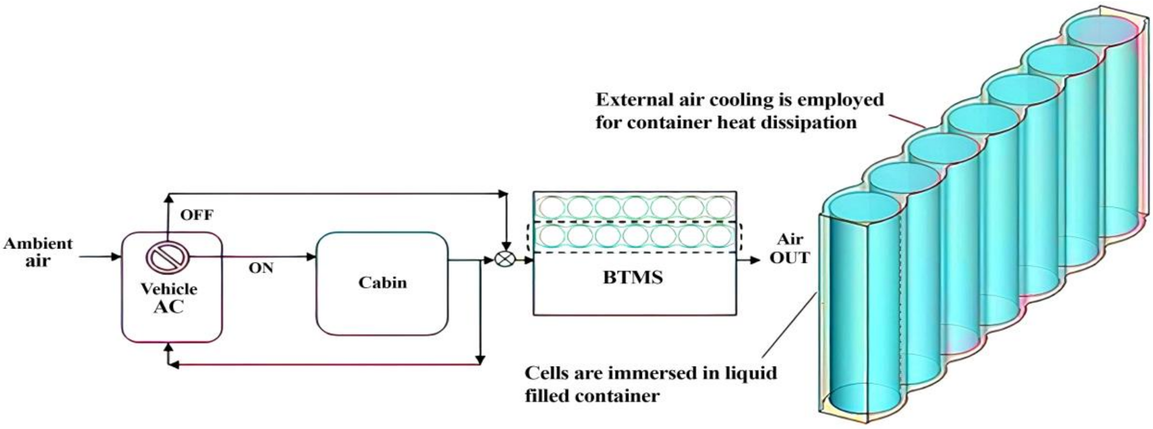

Figure 11. BTMS proposed with LfBS (refer to Reference (Jilte et al., 2019) with permission from Elsevier).

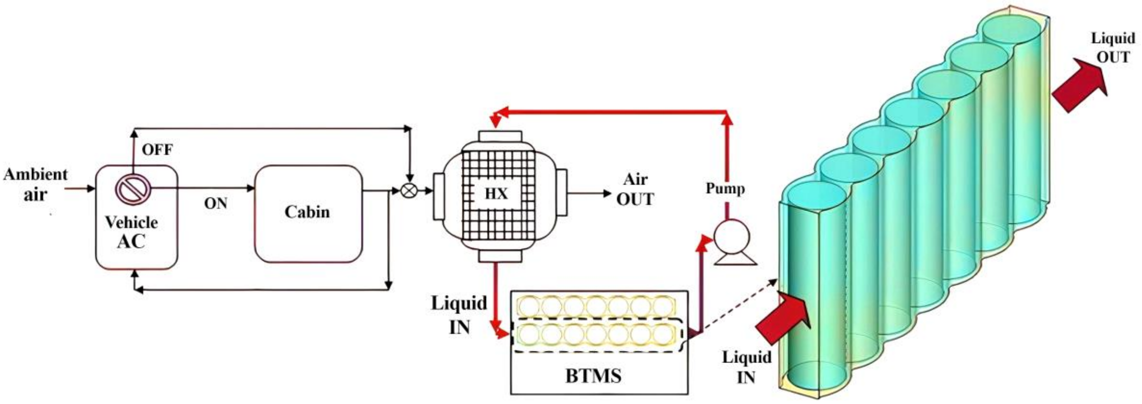

Figure 12. BTMS proposed with LcBS (refer to Reference (Jilte et al., 2019) with permission from Elsevier).

Table 4. Summary of work carried out on nanofluid-based BTMS of the battery pack.

References	Approach	Nano-additives & oncentrations	Base Fluid	Flow Channel Configurations	Battery Module Details	Concluding Remarks	Advantages and Disadvantages
Wiriyasart *et al*. (Wiriyasart et al., 2020)	Computational	TiO_2 & 0.25%, 0.50% by volume	Water	Corrugated mini-channel	Cylindrical Li-ion cell batteries type 18,650	Temperature distributions were most affected by coolant flow direction, mass flow rate, and coolant type. The maximum reduction in the surface temperature of the battery was 27.59% compared to conventional cooling. CuO NPs were also briefly investigated, but the results were similar to those of Al_2O_3. Despite the increased K, the addition of NPs had no significant effect on the module temperature.	Advantages: 1- Improved battery performance; 2- Reduced sulfation; 3- Lower maintenance. Disadvantages: 1- Higher cost; 2- Safety concerns; 3- Limited availability.
Mondal *et al.* (Mondal et al., 2017)	Computational	Al_2O_3 and CuO & 1% and 4% by volume	Water, EG-H_2O mixture	Rectangular microchannel	The module was made up of 20 prismatic cells that were divided into two or four stacks	This is due to a reduction in heat capacity when NPs are added, which decreases the amount of heat that can be discharged to the fluid at a given volumetric flow rate.	Advantages: 1- Improved battery performance; 2- Increased safety; 3- Cost-effectiveness. Disadvantages: 1- Potential side effects; 2- Limited research; 3-Manufacturing challenges

References	Approach	Nano-additives & concentrations	Base Fluid	Flow Channel Configurations	Battery Module Details	Concluding Remarks	Advantages and Disadvantages
Jilte *et al.* (Jilte et al., 2019)	Computational	Al_2O_3 & 0.4% (by volume	Water	Liquid-filled BTMS and Liquid circulated BTMS are the two types of arrangements considered	Small cylindrical cells	Nanofluids can be used in both arrangements to reduce the battery's temperature. The liquid-circulated arrangement enables EVs operating at higher discharge currents to remain within safe limits. Temperature uniformity in a liquid-circulated arrangement is superior to that in a liquid-filled arrangement. However, nanofluids do not dissipate enough heat to justify their use when compared to a base fluid like pure water.	Advantages: 1- Improved battery performance; 2- Longer battery life; 3- Cost-effectiveness; 4- Environmentally friendliness. Disadvantages: 1- Limited research; 2- Incompatibility issues; 3- Safety concerns.

5. CONCLUSION

BTMSs based on PCMs have recently garnered significant research attention due to their straightforward structure, exceptional temperature regulation, and low power usage. A significant challenge of PCMs was their poor Ķ, although adding metal, metallic oxides, and carbon-based nano-additives was found to improve the Ķ of the PCM. This has been thoroughly explored in recent studies and generally leads to enhanced efficiency in BTMS using nanocomposites. Alternative approaches for boosting heat transfer in phase change materials involve fins and metal foams. In some cases, PCM-based battery thermal management systems have considerably improved the thermal management of LIBs, while in other instances, inclusion of nano-additives has a modest yet favorable effect on heat transfer and lowering battery temperature. Researchers found that there was a trade-off between boosting Ķ improvement and suppressing N-C in nanocomposites, which can be utilized for the optimal performance of PCM-based BTMS.

Finally, the results obtained from the transactions are summarized as follows:

PCM $Na_2(SO_4)\cdot 10H_2O$ and Eicosane with nano additive Al_2O_3 NPs at 2%, 5%, and 10% are cost-effective and can help regulate the temperature of the battery, but they have a limited temperature range and energy storage capacity. They may be suitable for applications where a moderate level of thermal management is required.

PCM n-eicosane with nano additive Cu NP at ϕ_V: 3%, 5%, and 7% has improved thermal conductivity and energy storage capacity and can help regulate the temperature of the battery, but it also had a limited temperature range and thermal stability. It may be suitable for applications where more efficient thermal management is required.

Industrial-grade paraffin PCM with nano additive MWCNTs has improved thermal conductivity and heat capacity and can help regulate the temperature of the battery, but it has a limited temperature range and potential for leakage. It may be suitable for applications where a moderate level of thermal management is required.

Nano-additives TiO_2 & 0.25% and 0.50% by volume-based water have improved thermal conductivity and are non-toxic and environmentally friendly, but they have a limited energy storage capacity and temperature range. They may be suitable for applications where a low level of thermal management is required.

Nano-additives Al_2O_3 and CuO at 1% and 4% by volume-based Water, EG-H_2O mixture have improved thermal conductivity and heat capacity and can help regulate the temperature of the battery, but they also have a limited energy storage capacity and temperature range. They may be suitable for applications where a moderate level of thermal management is required, and a water-ethylene glycol mixture can be used.

Nano-additives Al_2O_3 at 0.4% by volume-based Water have improved thermal conductivity and are cost-effective and non-toxic, but they have a limited energy storage capacity and temperature range. They may be suitable for applications where a low level of thermal management is required.

Now that the effectiveness of using PCMs and nanoPCMs in BTMC has been demonstrated, although this technology has a long way to go, its unique ability to absorb and emit a large amount of heat makes it ideal for air conditioning and cooling systems of car cabins. In air conditioning, PCMs can store thermal energy during the day when temperatures are high and release that energy at night when temperatures are cooler. This reduces the need for energy-intensive cooling during the day and can help to reduce energy costs.

In car cabin cooling systems, PCMs can regulate temperatures and reduce the need for air conditioning. By incorporating PCMs into a car cabin's walls, seats, and ceilings, the material can absorb heat during the day and release it at night, keeping the car cool and comfortable. It's important to note that using PCMs in air conditioning and car cabin cooling systems is still a relatively new technology, and there are many factors to consider when designing and implementing these systems.

6. FUTURE DIRECTIONS AND PERSPECTIVES

The progress of today's science has provided a strong foundation for fast-charging batteries. However, fast charging results in a rapid increase in temperature in batteries, leading researchers to focus on improving the cooling effectiveness and energy dissipation in LIBs. While some studies have examined the implication of NP integration on the latent heat of PCMs, optimal conditions for Li-ion beyond Li-ion battery technologies (BTMS) using NP-based composite PCMs have yet to be thoroughly investigated. As reviewed, NP-based composite PCMs represent a promising solution for this industry due to their improved thermal properties.

Although considerable research has been conducted on BTMS, many areas for improvement remain. Future studies will undoubtedly focus on enhancing the cooling effectiveness and cooling mechanism rate and reducing the operating costs of BTMS.

7. ACKNOWLEDGEMENT

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NOMENCLATURE

LcBS	liquid filled BTMS
LfBS	liquid circulated BTMS
PCM	phase change material
NEPCM	nanoenhanced phase change materials
CPCM	composite phase change material
LIB	lithium-ion battery
MWCNT	multi-walled carbon nanotube
EV	electric vehicle
N-C	natural convection
EXG	expanded graphite
HEV	hybrid electric vehicle
HT	heat transfer
HTF	heat transfer fluid
LIB	lithium-ion battery
NP	nanoparticle
PHP	positive heat pole
BTMS	battery thermal management system
LH	latent heat
EG	ethylene glycol
C	discharge rate
CNTs	carbon nanotubes

$\hbar$	heat transfer coefficient
K	thermal conductivity ($Wm^{-1}K^{-1}$)
T_{amb}	ambient temperature (°C)
T_{max}	maximum temperature (°C)
T_{min}	minimum temperature (°C)
Φ_m	mass fractions
μ	viscosity
$\dot{q}$	heat generation rates (W)
ϕ_V	volume fractions
T_{avg}	average temperature (°C)

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