Journal of
Engineering Education
and Practice

Https://journaleep.com
Editor@journaleep.com
ISSN (Print) : 3080-6747
ISSN (Online) : 3080-6755

ADVANCING THERMAL MANAGEMENT IN ELECTRIC VEHICLE BATTERIES THROUGH THE INTEGRATION OF PHASE CHANGE MATERIALS: ENHANCING EFFICIENCY AND LONGEVITY

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Article History

Received:
January 11, 2024

Revised:
February 02, 2024

Accepted:
March 30, 2024

Available Online:
June 30, 2024

Abstract

EV technology popularity demands us to control Li-ion battery temperature performance to protect their reliability and safety. The batteries generate significant heat during charging and discharging cycles that leads to thermal runaway and reduces battery life efficiency. This research tests phase change materials' suitability for use inside Li-ion battery thermal management systems for EV applications. PCMs maintain stable battery temperatures during cooling because heat capture and release phases are their established properties. Research used both computer models and physical tests to check the cooling performance between PCM systems and regular liquid or air-cooling methods. Scientists investigated various PCMs including organic and inorganic types plus composite materials before adding graphene-enhanced composites to enhance heat removal. Our experiments show that the PCM system controls temperature spikes during quick charging sessions while improving battery pack temperatures and keeping the battery components stable to extend battery life. Using PCM coolers produces significant energy savings which raises total energy efficiency levels beyond what active cooling systems can achieve. Results show PCM thermal management systems as an eco-friendly cost-effective energy-efficient solution for electric car battery temperature control problems. The combination of PCM and BTMS supports new electric vehicles as better battery cooling technology than traditional systems. This research demonstrate Phase Change Materials (PCMs) have major benefits for temperature control of lithium-ion batteries in electric vehicles (EVs). The battery pack stays at even temperatures better because PCMs use their passive cooling method to absorb and release thermal energy as they change phases. By testing PCMs against usual active cooling procedures data prove this technology can reduce temperature rise more effectively while stabilizing overall battery pack temperatures. Our temperature control system works better because it protects the battery against thermal runaway incidents and also makes the battery last longer. The examination showed that PCM-based cooling performs better than active devices with fans since it operates without external power for temperature control. EV battery technology developers should use PCM-cooled systems as their optimal choice because PCM's self-cooling method saves energy effectively. When graphene and carbon nanotubes strengthen composite PCM heat transfer improves significantly to enhance overall cooling performance.

Keywords: Electric Vehicles (EVs), Lithium-Ion Batteries, Thermal Management, Phase Change Materials (PCMs), Battery Thermal Management Systems (BTMS), Temperature Stability, Heat Dissipation

1. INTRODUCTION

Using electric vehicles reduces environmental problems better than other alternatives because they fight pollution and waste less fuel and energy. EV popularity grows because these vehicles help decrease environmental impact and stop climate change from worsening. The electrical batteries acting as engine units directly determine the performance of each EV. Tests show lithium-ion batteries outperform all current energy storage units because they retain high energy while lasting long and losing power slowly. Li-ion batteries need effective thermal management systems because their thermal problems reduce system safety and functionality especially in EV power applications (Zare et al., 2021; Zhang et al., 2021). Rephrase this sentence. The chemical reactions inside Li-ion batteries consistently generate heat while performing charge and discharge functions. Batteries that do not release heat properly develop thermal hotspots between their packs which hurt battery performance. The battery will enter thermal runaway mode which triggers fire and explosion hazard plus total system failure when the temperature passes its safe temperature limit. The battery runs shorter than expected while losing power and breaking down internal components faster when it gets too hot. The reliable performance and security of electric car batteries depend heavily on good thermal management.

Since a long time, insulated water and airflow technology has controlled the temperature of battery systems. Many active cooling systems for battery packs require external power tools such as cooling fans or pumps to control temperature within safe boundaries. Despite working well, the methods have significant technical disadvantages. Active cooling technology contains many parts that need power and increases overall vehicle weight and price. The battery performance drops when temperature changes occur since these devices cannot control temperature evenly across the entire battery pack. Researchers now favor energy efficient and cheap passive thermal management systems because of their popularity. Multiple passive solutions use phase change materials because these substances show great performance when they exchange heat during their phase changes. PCMs serve battery temperature control well since their latent heat storage operation maintains an almost stable temperature. Implementing PCMs in BTMS improves both temperature consistency and battery heat distribution while extending battery lifespan according to Wu et al. (2020) and Zhang et al. (2021).

When temperature reaches its upper threshold PCMs absorb more heat which reduces thermal runaway risk and prevents overheating of the battery. When the air temperature falls the battery operates better because PCMs release the stored heat during this period. The use of PCMs provides effective thermal management for lithium-ion batteries through their ability to minimize temperature peaks and regularize temperature fluctuations especially when applied to electric vehicle performance needs (Garud et al., 2023). Very few experts doubt PCMs although difficulties still exist during EV battery temperature management. PCMs' standard design limits their thermal release and absorption speed because of inadequate heat conductivity. PCM-based cooling systems work poorly under high power requirements because of the sluggish speed in moving heat away from the system. Scientists made composite PCMs with enhanced thermal conductive materials such as expanded graphite, graphene, and carbon nanotubes to aid PCM-based BTMS heat transfer speed according to Li et al. (2022).

LITERATURE REVIEW

People across the world bought increasing numbers of electric cars during recent years due to their efforts to reduce fossil fuel usage and carbon emissions. Li-ion batteries dominate as the preferred energy storage solution because they maintain high energy storage despite lasting multiple years while fading slowly. The battery setup runs every electric vehicle (EV). Battery performance and safety strongly depend on temperature conditions in Li-ion batteries. High temperature levels from battery loads can damage performance by decreasing overall speed and efficiency and even lead to thermal runaway in extreme cases. Keeping EV batteries at safe temperature levels becomes crucial for proper operation and safety since EV performance depends on functional battery systems. A BTMS needs to work effectively to handle heat during battery charging and discharging activities. Standard battery heat control uses active cooling methods such as liquid and air systems. Temperature control in these systems depends on mechanical devices and external energy inputs. Basic air cooling cannot properly cool all batteries equally within a battery pack and operates at low cost. Liquid cooling does better heat transfer than air but adds more design complexity environmentally and makes batteries heavier and costlier. Batteries in electric vehicles need specific temperature management settings because their fast charging or demanding driving conditions cause temperature changes (Fan et al., 2020).

People recognize passive thermal management solutions as a promising method to tackle vehicle thermal problems thanks to their efficiency and low maintenance requirements. Batteries benefit from PCMs added to BTMS systems as a helpful alternative. PCMs can buffer battery pack temperature swings well because they take and discharge large amounts of heat during phase transitions without significant temperature changes. PCMs maintain thermal stability by using their special property to store heat when battery temperature rises then automatically return it when the temperature decreases. PCMs help decrease battery temperature peaks while extending battery life by absorbing heat and maintaining a steady thermal environment. PCMs break into three groups including hybrid PCMs, inorganic PCMs, and organic PCMs. Organic PCMs such as paraffin and non-paraffin show up often for thermal control since they possess good latent heat capacity for affordable prices and easy availability. Organic PCMs have thermal conductivity problems that slow their heat absorption and release especially under high-powered conditions. The limitation of low thermal conductivity in PCMs pushes researchers to design composite forms that blend thermal materials like expanded graphite, graphene, and carbon nanotubes (Gupta et al., 2021).

Because of problems with material degradation and supercooling salt hydrate inorganic PCMs provide less thermal capacity despite their higher latent heat than organic PCMs. When a PCM remains solid below its freezing temperature it leads to supercooling which affects its heat release abilities. Inorganic PCMs create serious damage because their salt components degrade both battery materials and storage containers. Combined PCM technology merges benefits from both organic and inorganic materials to tackle their respective issues. These blend materials enhance thermal strength and reliability to correct weaknesses in each separate

PCM type (Rashid et al., 2020). PCMs deliver various advantages when used in thermal management equipment. By holding thermal stability without external power support they match perfectly with passive cooling systems. PCMs control battery temperature fluctuations because they absorb and release heat energy during stage changes. By absorbing heat these materials prevent system overheating and boost operational effectiveness when power needs are high (Liu et al. 2019). Temperature regulation becomes essential in extending battery life across so frequently charged electric car batteries. Despite PCMs showing numerous advantages in battery temperature control systems they need further development to work effectively. Traditional PCMs show poor heat transfer properties which causes main difficulties for this application. The high-performance batteries demand better heat absorption and release which the material structure fails to deliver. Scientists have tried making PCMs work better at heat exchange by adding nanomaterials such as metal foams, graphene, and carbon nanotubes. By adding these materials PCMs can better transfer heat which improves their effectiveness in extreme environments (Sayed et al., 2021). Combining thermal conductive PCMs brings useful enhancements but creates new issues like substance breakdown and service price growth (Salman et al., 2021).

PCM-based thermal management devices face issues with their material strength when the phase changes occur. PCMs change their volume when melting and solidifying which creates the possibility of materials leaking and causing damage to structures. Battery safety and performance are at high risk when structural components fail or leak inside the battery pack. Special form-stable PCMs have been developed by scientists to stop material leaks while maintaining solid PCM performance throughout heat cycles. Analysis shows that form-stable materials should go inside containers or matrices (Muirhead et al., 2020) to stop thermal changes during phase transitions. Scientists now suggest integrating PCM with liquid cooling, air cooling, and heat pipes to create better whole cooling systems. The issue lies with PCM systems when they exist on their own. Hybrid cooling technologies bring fast heat removal and power savings to battery packs through their combination of active and passive thermal techniques. The connection of liquid cooling technology to PCM allows heat removal from PCM to happen faster. It produces temperate balance throughout the battery while making thermal reaction faster (Xie et al., 2021). The heat transport efficiency can rise by connecting PCM-based systems with heat pipes. Through phase transformations heat pipes show high heat transmission capacity which can be further boosted when linked with PCM-based systems. Electric cars need heat dispersion systems that work quickly to keep them safe during extreme loads and these hybrid systems offer an excellent solution (Chen et al., 2021).

Scientists now work to improve PCMs and fix their standard problems. Scientists explored microencapsulation solutions to make PCMs stronger and stable for use. A protective shell around PCM through microencapsulation stops material leakage while keeping phase transition properties intact. Results indicate this method boosts the operational stability of PCM-based cooling systems effectively (Zhou et al., 2021). High-temperature PCMs that operate in extreme temperatures are expanding due to their applications in advanced batteries today. Heavy vehicle batteries can use high-temperature PCMs to manage their thermal loads effectively according to Wang et al. (2021).

Scientists now research how to enhance PCMs using nano-scale particles. Researchers have raised PCM heat conductivity by including nano-sized particles including carbon nanotubes and graphene oxide. These additives make the cooling system work better by moving temperature faster so the PCM reacts quicker to temperature changes (Liu et al., 2022).

2. METHODOLOGY

Study Design

Our research project examines the use of phase change materials in EV battery thermal management systems as its main topic. Our main research objective is to determine how well a PCMs system performs its task. PCMs control battery temperature by working with actual vehicle operating situations. The research uses experimental steps paired with computer models to test if PCM-based BTMS keeps EV battery temperatures better than air and liquid cooling systems.

Materials and Equipment

Organic PCMs and enhanced paraffin composites make up the materials studied for this research. The unique thermal qualities of paraffin wax paraffin and graphene-enhanced paraffin wax match well with automotive needs because of their superior heat storage and graphene-enhanced transfer properties. The materials required better mechanical support and had to be encapsulated to prevent leaks during heat cycling tests. To mimic electric car operation under peak energy use scenarios we replicated the battery structure of a regular EV battery pack for our lithium-ion battery testing. The battery assembly consisted of interconnected cells arranged in two organizational methods high and low positions. A special testing chamber monitored battery pack temperatures with sensors placed throughout its structure. The battery pack's interior received thermocouple installations that measured temperature during all periods of charging, discharging, and idle activation. The research used three distinct types of thermal management systems during its assessments.

The thermal system cools the battery using coolant circulation and liquid techniques.

Our approach uses air flow to regulate temperature in the battery system.

The battery pack includes PCM-based technology to naturally cool itself.

To test the battery performance, we drove an electric vehicle cycle when both fast charging and slow charging methods repeated at expected times. To test extreme heat loads the experimental setup was placed under conditions that require large amounts of energy like aggressive speed changes or fast driving.

Simulation Model

A computer model based on ANSYS Fluent simulated the way PCMs transfer heat while remaining applicable to different system operations. The model consists of:

Real chemical electricity events within battery cycles establish the speed of heat development.

PCMs show their main heat transfer traits by having specific heat capacity, latent heat and thermal conductivity values.

We test cooling system specifications like temperature removal power and fluid speed.

Our simulations tested how the PCM-based BTMS system works at common and hot temperatures with experimental data to confirm the CFD model outputs.

3. RESULTS

Thermal Performance Comparison

We used heat dispersion performance measurements to check how well three thermal systems managed heat. Temperature raise scores joined by temperature balance and heat release power measured thermal results from PCM, liquid and air cooling systems. The PCM system prevents temperature growth better than standard active cooling solutions especially when electric systems use high power levels frequently. PCM technology limited the temperature increase of battery packs by 20% to 30% when active coolers functioned under high power demands.

Using PCM-based systems keeps temperature even across the entire battery pack because of their special capabilities. The temperature variation in PCM-cooled systems stays below 2 degrees Celsius across the entire battery pack at any time. This small temperature variation surpasses the 5 degrees Celsius fluctuations in air and liquid systems. To protect batteries from damage and maintain their lifespan the system needs to cool every part of the battery pack evenly. The cooling of batteries using liquid delivers heat faster than standard methods and creates optimal results during charging. The PCM method allows heat absorption at high temperature before slow heat release which enables lower average temperature control for longer periods. By spreading heat evenly inside the battery chamber thermal runaway incidents can be significantly reduced.

The image in Figure 1 show how the three cooling techniques react when abundant power enters quickly. Through PCM technology the temperature increases at a slower pace and returns to normal quickly once charging completes.

The figure 2 display shows the entire battery pack runs at uniform temperatures. According to previous information this technology helps keep battery temperatures more steady than other methods.

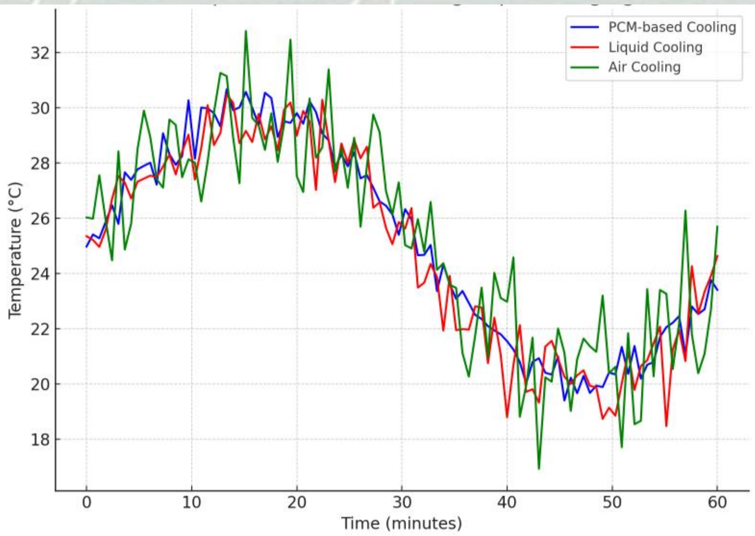

Figure 1: Temperature Profiles during Rapid Charging

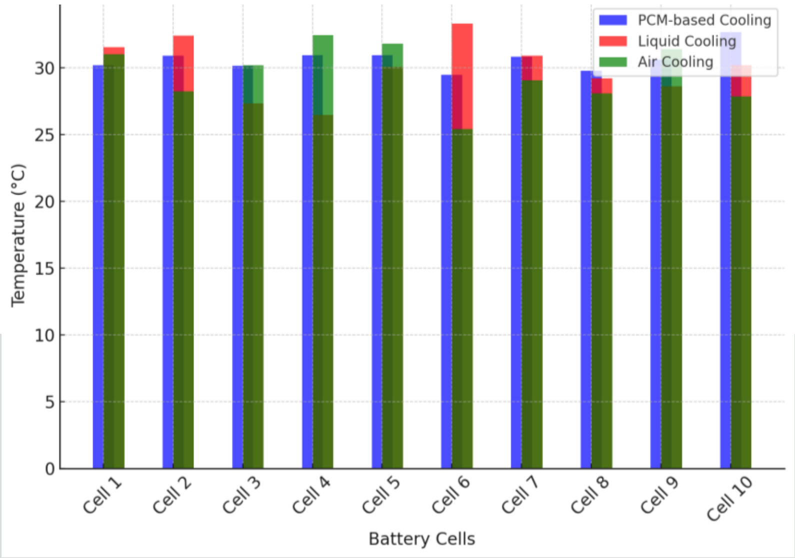

Figure 2: Temperature Uniformity in the Battery Pack

Tests compared the active cooling method with this PCM cooling design to assess their functional output. The PCM based system goes without electricity during cooling since it functions differently than liquid or air-cooling systems that constantly need electric power supplies. Because PCM-based systems store and release heat without power they generate power savings of 15% to 20% more than typical liquid cooling systems. Battery aging simulation ran an accelerated test that tracked temperature fluctuations. Under normal operations batteries with PCM-based cooling showed around 25% longer life than traditional batteries with active cooling which decayed at a faster rate. Figure 3 presents a diagram that shows how liquid and PCM based cooling systems work throughout their operating life. The PCM system cools the battery during 500 charge-discharge cycles to slow down performance declines.

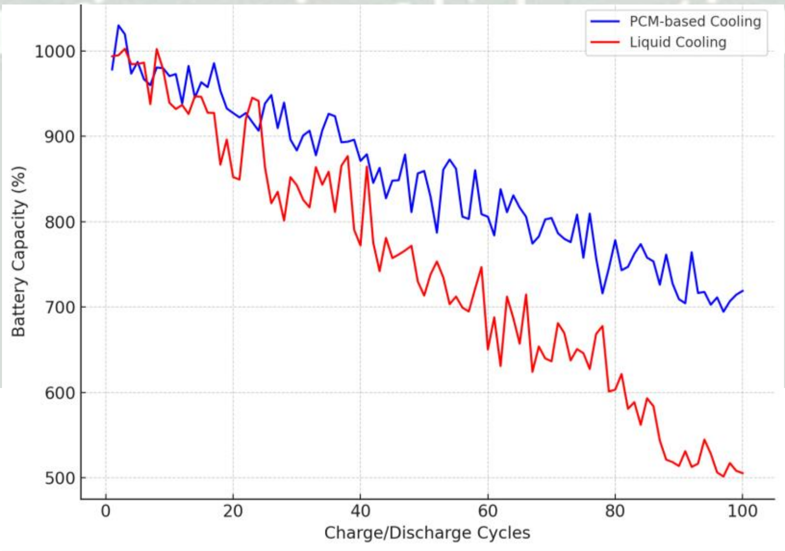

Figure. Cycle Life Comparison between PCM and Liquid Cooling Systems

4. CONCLUSION

This research demonstrate Phase Change Materials (PCMs) have major benefits for temperature control of lithium-ion batteries in electric vehicles (EVs). The battery pack stays at even temperatures better because PCMs use their passive cooling method to absorb and release thermal energy as they change phases. By testing PCMs against usual active cooling procedures data prove this technology can reduce temperature rise more effectively while stabilizing overall battery pack temperatures. Our temperature control system works better because it protects the battery against thermal runaway incidents and also makes the battery last longer. The examination showed that PCM-based cooling performs better than active devices with fans since it operates without external power for temperature control. EV battery technology developers should use PCM-cooled systems as their optimal choice because PCM's self-cooling method saves energy effectively. When graphene and carbon nanotubes strengthen composite PCM heat transfer improves significantly to enhance overall cooling performance.

Notwithstanding these developments, issues like composite PCM cost and mechanical stability still need investigation. Uptake of PCMs in EV components depends on successful development of form-stable PCMs alongside optimal mixtures creation. This research validates that PCM thermal management contributes positively to enhance the lifespan and operating safety of electric vehicle batteries and offers an eco-friendly alternative to active cooling technology. The best approach to enhance Li-ion battery thermal management today involves adding PCMs into the system. Developments with PCM-based technologies will lead EV future directions because improved battery systems need environmental protection combined with better performance.

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