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Electric Vehicle Battery Cooling Using Phase Change Materials and Nanofluids

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ABSTRACT

The phase change materials (PCM) and nanomaterials are employed to control overheating, which is the main problem of lithium-ion batteries. Due to its inherently low thermal conductivity, PCM struggles to dissipate heat from battery cells effectively. To address this issue, copper foam was incorporated to enhance its thermal conductivity. The battery temperature management system that utilizes phase change materials and nanomaterials is modeled in three dimensions through computational fluid dynamics (CFD) methodology. ANSYS CFD performed a steady-state thermal analysis with 378,000 nodes and 1.2 million elements based on suitable thermal boundary conditions. Phase change materials (PCMs) demonstrate superior performance compared to traditional cooling methods for keeping battery temperature within safe operational limits. Using passive cooling methods PCM-nanomaterial combinations deliver a low-cost maintenance-free solution which improves thermal efficiency and achieves consistent temperature distribution. This study employs paraffin wax as the phase change material and incorporates Al_2O_3 nanoparticles to act as a nanofluid additive. The selection of paraffin wax for electronic thermal management applications stems from its consistent thermal properties combined with its suitable melting point and substantial latent heat capacity. Experimental results combined with CFD simulations show that battery temperatures stay within the 15°C to 35°C range when using nanomaterials across multiple operating conditions.

1. INTRODUCTION

Improving the thermal management of electric vehicle (EV) batteries is the primary objective of this study so as to reduce the total cost of their cooling systems. Efficient temperature management is needed to keep the temperature of the battery pack within the optimal operation temperature (15-35°C). This paper presents an experimental and computational investigation of a lithium-ion battery model with Al_2O_3 nanoparticles and paraffin wax (as a phase change material, PCM added to improve the thermal performance).

The effectiveness of different battery cooling strategies is compared in terms of saving temperatures, running duration and cost-effectiveness. Electric motors, internal combustion engines and batteries are various types of power sources that hybrid electric vehicles (HEVs) employ.

Battery electric vehicles and plug-in hybrid electric vehicles have larger batteries and more components than traditional HEVs and can be recharged using regular electrical outlets. The rise of encouraging government policies and expanding international initiatives is fostering the growth and adoption of all types of vehicles. When measured against ICEVs, both HEVs and PHEVs benefit from higher fuel efficiency and environmental friendliness [1-3].

Material selection is essential when designing the battery thermal management system. Appropriate material properties include high specific heat and thermal conductivity, which will contribute to efficient absorption and dissipation of heat. The primary aim of thermal design is the removal of waste heat effectively from the battery system. Active cooling methods circulate a liquid or forced air to cool, but can be more complicated and energy intensive. Active cooling methods, on the other hand, consume additional energy sources, while passive ones employ natural convection, radiation or conduction mechanisms.

Because PCMs can store and release heat based on phase transitions and no longer require power to be utilized, passive solutions containing PCMs become more and more popular when designing the BTMS. They are thus an attractive alternative to conventional methods. It is unreasonable to use water based cooling for small battery modules due to the complex pipe network, and alternative solutions such as PCMs and thermoelectric devices are being researched. One of the promising approaches, which can provide an improvement of thermal conductivity and performance over other commonly used methods, such as air/liquid cooling or finned structures, is to add the nanomaterials to the PCMs.

2. METHODS FOR BATTERY COOLING

Electric automobiles (EVs) are being embraced as a cleaner opportunity to reduce the damage that CO_2 emissions reason to the environment, specifically when fossil fuels are used in the transportation sector. Lithium-ion batteries are important to EVs due to their steady performance over a large temperature range. However, these batteries produce a whole lot of heat once they charge and discharge, which, if no longer controlled, can shorten their lifespan.

Active, passive, and hybrid systems are the three principal classes into which Battery Thermal Management Systems (BTMS) fall. Among these, air-primarily based cooling structures are clean to use and reasonably priced, however they may be no longer as effective as liquid-based structures, which give superior thermal overall performance due to the higher unique heat and conductivity of fluids. However, liquid cooling systems are more complicated and need more parts, which raises the cost and upkeep needs. Phase change materials (PCMs) and heat pipes are two examples of passive techniques that provide a less expensive and maintenance-intensive option.

Significant heat is produced during vehicle operation, making effective thermal regulation necessary. Air cooling, fin-assisted cooling, liquid immersion or circulation systems, heat pipe mechanisms, evaporative cooling, mist and spray cooling, PCM-based thermal management, and the incorporation of nanomaterials are some of the cooling techniques that have been investigated for EV battery systems [4-8].

2.1 Air cooling systems

In these systems, air serves as the cooling medium. Through internal conduction and natural convection, heat is released from the battery into the surrounding air. Maintaining ideal battery temperatures is challenging because air has a low specific heat capacity and cannot absorb much heat, particularly in hot and dry climates [9-11].

2.2 Liquid cooling system

Liquid cooling is considered more effective than air due to the fluid's superior thermal properties and higher heat capacity. In direct-contact systems, the battery cells are submerged in a low-conductivity liquid. In indirect systems, heat is transferred through metal interfaces or channels. The type of liquid used can be selected based on the specific thermal demands of the battery system.

2.3 Fin cooling method

Fin structures are employed to increase the effective surface area for heat dissipation from the battery pack. These extended surfaces facilitate heat transfer via both conduction and convection. Fins can be designed in various shapes, such as rectangular or circular, and fabricated from thermally conductive materials. Their thermal behavior can be modeled based on length and boundary conditions—such as short fins, insulated-end fins, or infinitely long fins. This method, widely used in electronics and internal combustion engine vehicles, serves as a supplemental cooling strategy for battery systems [12, 13].

2.4 Heat pipe-assisted coolant method

A heat pipe, often described as a two-phase heat transfer device, is known for its ability to transport heat efficiently over a distance with minimal temperature loss. It is widely regarded as one of the most effective passive thermal management technologies. Typically, a heat pipe consists of a sealed container partially filled with a working fluid that exists in both liquid and vapor phases.

Heat from the battery causes the working fluid in the pipe's evaporator section to absorb energy and change phases through evaporation. The thin liquid film lining the inner surface of the evaporator boils and evaporates, propelling this process. After that, the vapor travels to the condenser section, where it transforms back into a liquid by releasing its latent heat. The cycle is completed when the condensed liquid returns to the evaporator section thanks to a capillary wick structure inside the pipe. Rapid and effective thermal regulation is made possible by this mechanism. Because heat pipe-based systems are small, dependable, and passive, they have been widely used to control the thermal performance of both cylindrical and prismatic battery cells.

2.5 Evaporative cooling technique

Evaporative cooling is based on the principle that energy must be absorbed to convert a liquid (typically water) into vapor at a constant temperature. During this phase transition, the required latent heat is drawn from the surrounding environment—specifically from air molecules—which results in a noticeable temperature reduction of the surrounding air.

When water is sprayed or dispersed into the air, it evaporates by extracting heat energy from the air, thereby reducing its temperature. This process has been observed to offer effective cooling in various thermal management applications. However, its integration into battery thermal control systems remains relatively underexplored.

Some experimental studies have shown that applying fine mist cooling under thermal stress conditions—such as thermal runaway—can boost cooling performance by over 46% compared to conventional air cooling. Evaporative cooling methods are typically categorized into three configurations: direct evaporative cooling, where water directly interacts with the air; indirect evaporative cooling, which uses a heat exchanger to separate the air and water streams; and combined systems, which integrate both direct and indirect approaches for improved performance.

2.6 Mist and spray cooling technique

Studies have shown that replacing active air cooling with mist-based cooling can dramatically enhance thermal management, reducing the thermal resistance of a heat sink by more than 97%. Key variables influencing the efficiency of droplet evaporation—and thereby the overall performance of mist cooling—include the initial droplet size and the concentration of misting fluid introduced.

Experimental investigations into the effect of mist cooling on cylindrical lithium-ion cells with nickel-manganese-cobalt (NMC) chemistry have demonstrated promising results. Under a variety of initial temperature conditions, mist cooling was found to significantly reduce the risk of thermal runaway, lowering the critical runaway temperature by approximately 36℃.

A 3D model of a battery thermal management system (BTMS) incorporating multiple nozzles positioned in the airflow direction was developed for a module consisting of six prismatic cells. As water is expelled through the nozzles, it breaks into fine droplets, forming a cone-shaped spray. These droplets travel with the airflow, evaporate, and in doing so, reduce the surrounding air temperature. The increased temperature gradient between the battery and the cooler air improves heat dissipation from the battery pack.

In comparison to conventional dry cooling, spray cooling has been shown to more effectively reduce peak cell temperatures. Incorporating spray cooling into a BTMS can help maintain a more uniform temperature distribution across the battery pack. Experimental and theoretical analyses under high discharge conditions confirmed its benefits. Results indicated that the heat transfer coefficient of spray cooling could be up to four times greater than that of forced air systems. Moreover, spray cooling turned into capable of restriction temperature version inside five °C, and the peak temperature remained beneath 10. three °C.

Additionally, assessed turned into a hybrid thermal control device that blended a flat heat pipe and a water spray mechanism. High discharge prices were used to test battery packs with capacities of three and eight mAh. With a temperature differential of much less than 1.5°C, the hybrid machine outperformed compelled air and passive convection cooling. Additionally, the machine validated short thermal recuperation following high-price discharge, successfully bringing the battery temperature back to baseline. Furthermore, higher thermal regulation in the course of the heating and cooling cycles was finished through combining section exchange substances (PCMs) with water spray and heat pipe cooling [14-18].

2.7 Phase change materials

During segment transitions, normally among solid and liquid states, PCMs take in and launch thermal power. The material absorbs warmth as sensible electricity because the temperature rises, and while it reaches its melting factor, it absorbs warmness as latent power. The cloth solidifies and releases the heat that has been saved when the temperature drops under this point. By retaining battery temperatures inside a safe and powerful operating variety, PCMs are able to make certain uniform thermal distribution across battery cells, that's in particular important in electric powered cars.

Relatively low melting point, excessive latent warmness potential, sufficient thermal conductivity, chemical stability, and affordability are all important for an efficient PCM for battery thermal control.

2.7.1 Paraffin wax as a PCM

- Because of its solid thermal traits and high latent heat of fusion, paraffin wax is often utilized in thermal control structures. It is suitable for uses requiring gradual heat alternation, together with digital cooling, sun storage, and constructing insulation, due to the fact it could take in or release sizable amounts of electricity with simplest slight temperature adjustments.
- Paraffin wax has numerous critical residences, consisting of:
  • High Latent Heat of Fusion: It correctly shops and releases warmth, preserving thermal equilibrium with little temperature fluctuation.
- Non-corrosive and non-toxic: safe for use in sensitive settings and for coping with.
- Broad Melting Point Range: To accommodate various operational necessities, it's far provided in more than one grades. Low Thermal Conductivity: Provides good insulation, though conductive additives can occasionally improve it.
- Thermal Storage Capacity: Has a latent heat of around 210 J/g and a melting range of 50–59°C.
- Chemical Compatibility: Does not react adversely with most construction or container materials. Without supercooling, it's miles possible to freeze without going into a metastable nation.
- Affordability and Availability: Generally less expensive than different PCM substitutes, consisting of salt hydrates, and easily sourced.
- In order to improve the thermal regulation properties of coatings, textiles, and building materials, paraffin wax is frequently utilized in microencapsulated shape. Paraffin wax is seemed as one of the most useful PCM options because of its wide range of programs.

Although a variety of waxes can be used as PCMs, paraffin is particularly prized for its potent thermophysical properties and affordable price. Electronic devices, solar collectors, incubators, desalination units, and thermal insulation for pavements and buildings are just a few of the many uses for it. Paraffin wax has a 5–14 times higher storage capacity than traditional thermal storage media like water or stone [19, 20].

2.7.2 Types of PCM phase transitions

PCMs use a variety of phase changes to store and release energy.

• Solid–Solid: Refers to structural alterations in the solid phase that are either crystalline or molecular. This kind of PCM is utilized in specialized applications such as non-volatile memory and exhibits minimal volume and energy fluctuations.

• Solid–Liquid: The most popular transition in commercial thermal management, it provides controlled volume changes and a large energy storage capacity.

• Liquid-gas and solid-gas: Despite having a large heat storage capacity, these systems are usually impractical for enclosed or compact systems due to their significant volume expansion.

2.7.3 Organic PCMs

Because of their chemical stability and dependability over a wide range of heat cycles, organic materials—particularly paraffin and non-paraffin compounds—are utilized extensively among PCM types [21]. In general, organic PCMs do not show signs of phase separation or supercooling, and they continue to function reliably even after repeated use. The main criteria used to classify these materials are their chemical makeup and intended use.

2.7.4 Paraffin chemistry and non-paraffinic PCM overview

The chemistry of paraffin is referred to in passing on this phase, but the essential attention is on its segment change capacity with a view to preventing repetition in the discussion of paraffin-primarily based section change materials (PCMs) [22]. Despite the great use of paraffin, non-paraffinic natural PCMs are also being investigated extensively due to their unique properties [23, 24]. These include materials that have been very well researched by researchers for thermal strength garage, consisting of fatty acids, alcohols, glycols, and unique ethers. Notwithstanding their capability, those materials often have disadvantages which includes high flammability, oxidation susceptibility, and relatively low thermal conductivity [25-27].

Particularly noteworthy are non-paraffinic natural PCMs like fatty acids, sugar alcohols, and polyols. For instance, fatty acids, which are chemically represented as $CH_3(CH_2)_{2n}COOH$, have a high latent heat and are occasionally combined with paraffin to improve thermal performance. They do not show supercooling during phase transitions and remain chemically stable over a wide range of thermal cycles. Cost is a major drawback, though, as fatty acids are typically two to three times more costly than technical-grade paraffins. Furthermore, even though they come from renewable resources like plants and animals, in some circumstances they may be mildly corrosive [28].

2.7.5 PCM selection guidelines and applications of paraffinic PCMs

Selecting an appropriate PCM requires careful consideration of multiple factors beyond just the phase transition temperature. These include thermodynamic, kinetic, and chemical properties, material availability, and economic viability. Sometimes, blending different PCMs or adding thermal enhancers may be necessary to meet performance requirements [29].

Key criteria for selection include:

- Appropriate Phase Change Temperature: Critical for matching application needs.
- High Latent Heat: Enables compact storage of thermal energy.
- Thermal Conductivity: Affects how efficiently energy is absorbed and released.
- Phase Stability: Ensures consistent energy storage over repeated melting/freezing cycles.
- Volume and Vapor Pressure Control: Important for minimizing material degradation during thermal cycling.

These attributes form the foundation of a hierarchical selection model. At the base are economic and regulatory factors, followed by thermal endurance and material compatibility. At the top are cycle life, reliability, user safety, and application-specific suitability. These guidelines are equally relevant for paraffinic PCMs (PPCMs).

2.7.6 Applications of paraffinic PCMs (PPCMs)

PPCMs are employed across various sectors including solar energy systems, food and pharmaceutical storage, electronics protection, automotive components, and building materials [30-36]. Their usage generally falls into two major application types:

- Thermal Energy Storage
- Thermal Protection

For thermal protection, PPCMs are essential in packaging and transporting temperature-sensitive products such as vaccines, medical devices, and perishable food [37, 38]. Their ability to regulate internal temperatures within defined thresholds makes them ideal for cold chain logistics and electronics protection. For example, one study demonstrated that applying a paraffin coating on resistor chips extended overheating delay times by 50-150% within the temperature range of 110-140°C [39]. Another experiment incorporated a blend of paraffin and polypropylene into solar collectors as an overheating safeguard [40].

The more essential utility location, but, lies in passive strength garage, wherein PPCMs feature without external energy enter. Most studies on this area focuses on their integration in sun thermal structures, textiles, and specially in building substances. Lightweight construction materials often be afflicted by bad warmth retention, main to substantial indoor temperature swings. By embedding PPCMs, it will become viable to stabilize internal temperatures, buffering in opposition to external thermal fluctuations and enhancing average strength efficiency [41].

2.7.7 Applications of paraffinic PCMs in buildings and battery thermal management

For passive thermal law, paraffinic section exchange substances (PPCMs) are frequently included into constructing systems. When the temperature is excessive during the day, they take in and shop warmness, which they then release at night time when it's miles cooler. By lowering indoor temperature swings, this technique improves thermal consolation whilst using less electricity for heating and cooling.

Certain kinds of PCMs are used in a few HVAC systems to hold temperatures under freezing. To maintain a cooler indoor surroundings all through the most up to date parts of the day, these systems save cool energy at night time and release it at some stage in the day.

PPCMs were applied in numerous building components, which include thermal insulation in partitions, ground heating structures, ceiling panels, sun air heating units, passive cooling structures, and thermal shutters [42]. When encapsulated or modified to be shape-strong, PPCMs may be correctly included into structural elements like gypsum forums and concrete, supplying thermal storage without compromising material integrity [43-46].

Further studies have evaluated the integration of liquid cooling methods with PCMs to enhance thermal regulation [47-49]. Innovations in this area include the use of metal foam matrices and miniature channel designs, which help to optimize heat transfer in battery cooling systems [50]. Another study demonstrated the use of annular thermoelectric coolers in conjunction with PCMs, where numerical simulations were employed to assess their efficiency [51-53]. The influence of temperature on battery operation has been a key focus of such investigations [54].

Comparative assessments between strong and perforated pin-fin warmness sinks have proven that the latter promises more effective thermal management, offering progressed warmness dissipation traits [55-57].

Because of its excessive latent heat capacity, moderate melting point, chemical inertness, and non-corrosiveness, paraffin wax remains the most famous PCM for electronics cooling. However, due to its terrible thermal conductivity, which limits its overall performance, scientists are operating to boom its effectiveness through adding thermally conductive substances like metallic foams and nanoparticles. In order to mitigate the flammability issues associated with paraffin-primarily based PCMs, flame retardants have additionally been introduced in loads of formulations. Collectively, those tasks highlight the increasing significance and improvement of PPCMs in thermal law and power garage systems.

2.7.8 Enhancement of PCMs using nanoparticles

Nanoparticles are crucial for enhancing PCMs' thermal performance. Because of its high thermal conductivity, affordability, and chemical balance, aluminum oxide (Al_2O_3) is one of the maximum extensively used of them. It may be used as a catalyst or adsorbent in chemical reactions as well as a base cloth in electronics because of its amphoteric nature and insulating features. When integrated into PCMs, Al_2O_3 significantly enhances heat transfer, facilitating faster charging and discharging cycles during phase transitions. Unlike standard storage materials, PCMs can absorb and release thermal energy at rates 5 to 14 times higher, making them highly efficient for latent heat applications.

2.7.9 Experimental setup for PCM-based battery cooling

To evaluate the effectiveness of PCM-nanomaterial systems in battery cooling, a custom experimental apparatus was constructed, as depicted in Figure 1. The system incorporates copper foam, selected for its high porosity (~98%) and fine structural features, which collectively enhance thermal conductivity.

A 240 V, 500 W heater served as a heat source, chosen for its ability to generate consistent and rapid thermal output, emulating the heat produced by a 48 V, 35 A electric vehicle battery. While actual batteries take longer to reach equivalent thermal loads, the heater enabled more efficient testing in a controlled environment.

The thermal behavior and comparative efficiency of various PCMs used in this setup are summarized in Table 1, highlighting differences in storage capacity, conductivity, and responsiveness during thermal cycling.

Figure 1. Experimental setup for battery cooling

Table 1. Specifications of PCM

Properties	Paraffin Wax	Non-Paraffin	Hydrated Salts	Metallics
Melting Point (°C)	-20-100	5-120	0-100	150-800
Latent Heat (kJ/kg)	200-280	90-250	60-300	25-100

3. ANALYSIS FOR BATTERY COOLING

3.1 CAD model preparation

The analysis can be performed for different domains such as structural, heat transfer, fluid flow, mass transfer, electronics, etc. The CAD model is prepared using CATIA for analysis as shown in Figure 2.

3.2 Computational fluid dynamics (CFD) of battery

The analysis is performed with the help of ANSYS CFD for battery cooling to understand the heat and fluid flow around the battery. In CFD, the conservation of mass, momentum, and energy is studied by converting partial differential equations into algebraic equations, which are solved by high-speed computers. The CFD is divided into preprocessor, solver, and post-processing. In preprocessing, CAD geometry is prepared with CATIA, mesh the geometry, and boundary conditions are specified, while in the solver, the turbulence model is selected for analysis, and post-processing is performed for visualization of various plots such as pressure, temperature, and heat transfer coefficient under steady state conditions. Figure 3 shows battery geometry with mesh for CFD analysis, and Figures 4 and 5 suggest maximum and minimum temperatures in the battery with 378660 nodes.

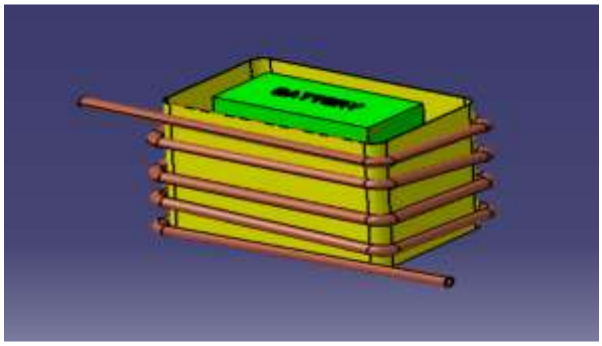

Figure 2. CAD model for battery

Figure 3. Battery geometry with meshing for CFD analysis

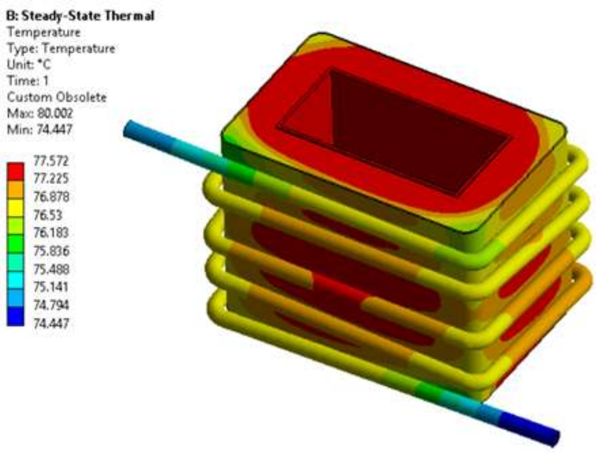

Figure 4. Thermal analysis of the battery

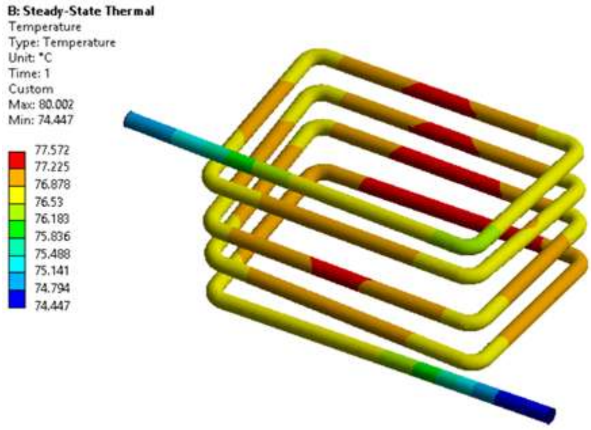

Figure 5. Temperature locations along the battery

4. CONCLUSIONS

Battery lifespan is a critical factor in the automotive industry, largely due to cost concerns. One major challenge is the gradual decline in battery efficiency over time, along with the environmental impact associated with recycling electric vehicle (EV) batteries. Given the limited space and time available at charging stations, it is important that EV batteries can be recharged quickly. Cooling systems are implemented not only to manage temperature but also to reduce vibrations, thereby enhancing overall battery performance.

Research shows that the rate of heat generation inside a battery increases with higher discharge rates. In recent studies, aluminum oxide (Al_2O_3) nanofluids have been used alongside paraffin wax as a phase change material (PCM) to improve thermal management. These materials help maintain controlled temperatures within the battery compartment, with surface temperatures observed to range from approximately 20 to 35°C under various conditions. However, the inherently low thermal conductivity of PCMs can lead to slower heat dissipation and uneven temperature distribution, which may negatively affect battery health. Additionally, the limited specific heat capacity of PCMs, both in solid and liquid phases, can cause sharp temperature rises in the battery pack when the PCM temperature is below its melting point. Higher total pack temperatures may arise from the increased thermal resistance between the coolant and the battery caused by PCMs. In general, air cooling systems are unable to effectively or consistently regulate battery temperature. Because of the necessary piping networks, liquid cooling adds complexity even though it is more efficient and provides better temperature uniformity. When employing PCM and nanofluids for thermal management, experimental and computational fluid dynamics (CFD) studies show that, at steady state, temperatures throughout the battery stay within acceptable bounds.

Heat pipe-assisted BTMS can handle a variety of coolants and are efficient at transferring heat. However, the small contact area with the battery surface limits their performance.

BTMS that rely solely on pure coolant mediums exhibit certain drawbacks, including insufficient heat dissipation. Consequently, using hybrid coolant systems—combining multiple cooling media—is considered the most promising approach for optimization. Techniques such as evaporative cooling, mist or spray cooling, and adding nanoparticles to the coolant have demonstrated potential in meeting BTMS goals related to cost-effectiveness, low energy consumption, sustainability, and high cooling performance.

When designing EV thermal management systems, environmental impacts must also be factored in. Using hybrid coolants enhanced with eco-friendly, non-toxic, readily available, and affordable materials—such as jute pads, wick filters, and hydrophilic fibers—can improve both the sustainability and efficiency of these systems.

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NOMENCLATURE

BTMS	Battery Thermal Management System
CFD	Computational Fluid Dynamics
CPCM	Composite Phase Change Material
EV	Electric Vehicle
EDVs	Electric Drive Vehicles
FEM	Finite Element Method
LIB	Lithium-Ion Battery
PCM	Phase Change Material
PDE	Partial Differential Equation
PPCM	Paraffinic PCM