Nano-filler Reinforced Phase Change Composites: A Pathway to Next-Generation Thermal Regulation

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Abstract. The rapid development of new energy vehicles and the increasing demand for high-performance batteries highlighted the urgency of efficient battery heat dissipation. This paper aimed to systematically study how various nano-fillers, including metal-based, metal oxide-based and emerging nanomaterium-based NePCM, enhanced the heat dissipation performance of phase change materials. Through in-depth research on the application cases of different NePCM in the thermal management system of new energy vehicle batteries, and a comprehensive comparative analysis of their thermal conductivity, stability and cost-effectiveness, the practical application effect was evaluated. The results showed that each type of nanomaterials had unique advantages: metal-based fillers exhibited high thermal conductivity, while emerging nanomaterials demonstrated potential for multifunctional performance. However, they also faced challenges such as cost and compatibility. Based on these findings, practical suggestions for optimizing the application of NePCM were proposed, which could guide the development of more efficient battery heat dissipation solutions.

Keywords: new energy vehicles, NePCM, battery heat dissipationr.

1. Introduction

In the global automotive industry landscape, the rapid development of new energy vehicles constituted a transformative force. According to data from the International Energy Agency (IEA), in 2023 alone, global sales of electric passenger vehicles exceeded 14 million units, representing a year-on-year growth of over 35%. The proliferation of new energy vehicles was not only driven by the urgent need to mitigate climate change but also by technological progress, which enhanced their competitiveness in terms of performance and price. As the market share of new energy vehicles expanded, the demand for high-performance batteries reached an unprecedented level. These batteries were expected to deliver high energy density, extended driving range, robust safety features to mitigate risks, and cost-effectiveness to facilitate mass-market adoption.

Lithium-ion batteries had firmly established themselves as the cornerstone of power for new energy vehicles due to their significant advantages [1]. Compared with traditional battery technologies, they offered higher energy density, enabling new energy vehicles to achieve ranges that were once considered unattainable. For instance, some of the latest electric vehicles could travel over 600 kilometers on a single charge, a capability attributed to the enhanced energy storage capacity of lithium-ion batteries. Furthermore, these batteries demonstrated a relatively long cycle life, withstanding hundreds (if not thousands) of charge-discharge cycles without significant performance degradation. Their low self-discharge rate ensured energy retention, providing reliable power when needed. However, the continuous pursuit of maximizing energy density raised a critical challenge: heat dissipation.

During the operation of lithium-ion batteries, complex chemical reactions occurred, generating heat as a byproduct. When heat production exceeded dissipation rates, thermal accumulation occurred within the battery pack. This phenomenon accelerated the degradation of battery materials, such as electrodes and electrolytes, leading to reduced capacity and efficiency over time. Temperature increases caused fluctuations in internal resistance, resulting in inconsistent power output and diminished driving performance. In extreme cases, overheating triggered thermal runaway—a chain reaction characterized by rapid temperature escalation, potentially leading to fires or explosions.

Notably, several thermal runaway incidents involving new energy vehicle batteries had been reported in recent years, causing significant property losses and fatalities. These incidents highlighted the urgency of effective thermal management [2].

Phase change materials (PCMs) emerged as a promising solution to lithium-ion battery heat dissipation challenges. The working principle of PCMs involved absorbing and releasing latent heat during phase transitions, such as solid-to-liquid transformations, enabling thermal energy regulation. Nano-enhanced phase change materials (NePCMs), which integrated nanoscale fillers into PCM matrices, demonstrated extraordinary potential in enhancing thermal conductivity. For example, it is reported that carbon-based nano-fillers (e.g., graphene nanosheets) in paraffin-based PCMs increased thermal conductivity by up to 400% [3]. Similarly, it is found that metal-based nano-fillers, such as silver nanoparticles, enhanced both thermal conductivity and mechanical properties of PCMs [4]. These findings stimulated further exploration of NePCM applications in battery thermal management systems.

This study conducted a comprehensive exploration of NePCM applications in new energy vehicle battery thermal management systems. In the case description section, the definitions and characteristics of metal-based, metal oxide-based, and emerging nanomaterium-based NePCMs were analyzed. Metal-based NePCMs were discussed for their high thermal/electrical conductivity and challenges such as corrosion risks. Metal oxide-based NePCMs were evaluated for their thermal stability and chemical inertness, while emerging nanomaterium-based NePCMs were explored for their multifunctional properties. The problem analysis section assessed each NePCM type's performance in real-world scenarios, considering thermal conductivity, long-term stability, cost-effectiveness, and environmental impact. A comparative table in the recommendations section summarized the advantages and limitations of different NePCMs, accompanied by practical guidelines for material selection. Finally, the conclusion synthesized key findings, emphasized NePCMs role in advancing thermal management technologies, and proposed future research directions in this field.

2. Case Description

2.1. Metal-Based NePCMs

Metal-based NePCM was a kind of nano-phase change material in which metal nanoparticles were incorporated into the matrix of phase change materials. These metal nanoparticles were usually made of materials such as copper, silver or aluminium and were dispersed in nanoscale fundamental phase change materials. The decisive feature of metal-based NePCM lay in its excellent thermal conductivity. Metals were renowned for their high thermal conductivity. When they were reduced to the nanoscale and integrated into PCM, they significantly enhanced the overall heat transfer efficiency of the composite materials. This characteristic made metal-based NePCM highly suitable for applications that required rapid heat dissipation, such as thermal management of high-power lithium-ion batteries in new energy vehicles. In addition, metal nanoparticles could also enhance the mechanical strength of the PCM matrix to a certain extent, improving its durability and stability during use.

2.2. Metal Oxide-Based NePCMs

Metal-based NePCM was a kind of nano-phase change material in which metal nanoparticles were incorporated into the matrix of phase change materials. These metal nanoparticles were usually made of materials such as copper, silver or aluminium and were dispersed in nanoscale fundamental phase change materials. The decisive feature of metal-based NePCM lay in its excellent thermal conductivity. Metals were renowned for their high thermal conductivity. When they were reduced to the nanoscale and integrated into PCM, they significantly enhanced the overall heat transfer efficiency of the composite materials. This characteristic made metal-based NePCM highly suitable for applications that required rapid heat dissipation, such as thermal management of high-power lithium-ion batteries in new energy vehicles. In addition, metal nanoparticles could also enhance the mechanical strength of the PCM matrix to a certain extent, improving its durability and stability during use.

2.3. Emerging Nanomaterials-Based NePCMs

Emerging nanomaterials - NePCM was a type of nano-phase change material that utilized new advanced nanomaterials, such as graphene, carbon nanotubes, and metal-organic frameworks (MOFs). These emerging nanomaterials possessed unique physical and chemical properties. For instance, graphene and carbon nanotubes possessed extremely high thermal conductivity, electrical conductivity and mechanical strength at the nanoscale. Adding them to PCM not only significantly improved thermal conductivity but also endowed the composite material with additional functions, such as enhanced electrical performance or better mechanical flexibility. On the other hand, the metal-organic framework had a high surface area and adjustable pore structure, which could be used to optimize the heat storage capacity and heat transfer performance of PCM. NePCM based on emerging nanomaterials represented the cutting-edge research in this field and had great potential for innovative breakthroughs in the thermal management of new energy vehicle batteries.

3. Problem Analysis

3.1. Metal-Based NePCMs

The characteristic of metal-based NePCM was its remarkable thermal conductivity, which initially attracted battery thermal management. However, their application in the batteries of new energy vehicles was full of challenges. One of the most urgent problems was the corrosion problem. In the complex electrochemical environment of lithium-ion batteries, which contained electrolytes and trace amounts of moisture, metals like copper and silver were highly prone to oxidation [5]. For instance, copper nanoparticles, when exposed to the electrolyte of a battery, could gradually form a copper oxide layer on their surface. This oxidation not only reduced the effective thermal conductivity of the nanoparticles, but also released metal ions into the electrolyte. These metal ions would participate in unnecessary chemical reactions, such as depositing on the battery electrodes, which would lead to a decrease in battery capacity and an increase in internal resistance over time.

Cost was another significant obstacle for metal-based NePCM. The production of high-purity metal nanoparticles required complex synthesis techniques, including chemical vapor deposition and physical vapor deposition. These processes required expensive equipment, high-quality raw materials and strict operating conditions, resulting in a high cost per unit mass of nanoparticles. For instance, silver nanoparticles, due to the high cost of silver itself and the complexity of their synthesis, could make metal-based NePCM overly expensive in large-scale battery manufacturing. This cost factor severely restricted their wide adoption, especially in the highly competitive new energy vehicle market.

In terms of safety, the conductivity of some metal nanoparticles posed a risk. If the metal nanoparticles were not uniformly dispersed in the phase change material matrix, or during the operation of the battery, if the PCM matrix was damaged, the metal nanoparticles might come into contact with different parts of the battery circuit, thereby causing a short circuit. This kind of short circuit could cause rapid heat generation and potentially lead to thermal runaway, which was a serious safety hazard for lithium-ion batteries. In addition, during the charging and discharging cycles of the battery, mechanical stress and vibration could cause metal nanoparticles to migrate within the PCM, further increasing the risk of electrical contact problems.

3.2. Metal Oxide-Based NePCMs

Metal oxet-based nano-reinforced phase change materials (NePCMs) are composite systems formed by dispersing metal oxide nanoparticles (such as alumina, titanium dioxide, silicon dioxide, etc.) in a phase change material (PCM) matrix. The preparation of these materials usually adopts a combination of physical adsorption and cascade mixing methods to solve the problem of uneven dispersion caused by the density difference between nanoparticles and PCM matrices [6]. Take silicon dioxide (SiO_2) -modified paraffin-based PCM as an example. Firstly, the blocky solid paraffin is crushed into particles, and then it is uniformly stratified with the pre-treated metal oxide nanoparticles in a pre-set proportion. The material is heated in a high-temperature oven to melt it, allowing the nanoparticles to completely adsorb the phase change matrix. Subsequently, the nanoparticles were uniformly dispersed in the molten PCM through constant-temperature magnetic stirring, and a stable composite phase change material was obtained after cooling. The preparation process was shown in Fig. 1.

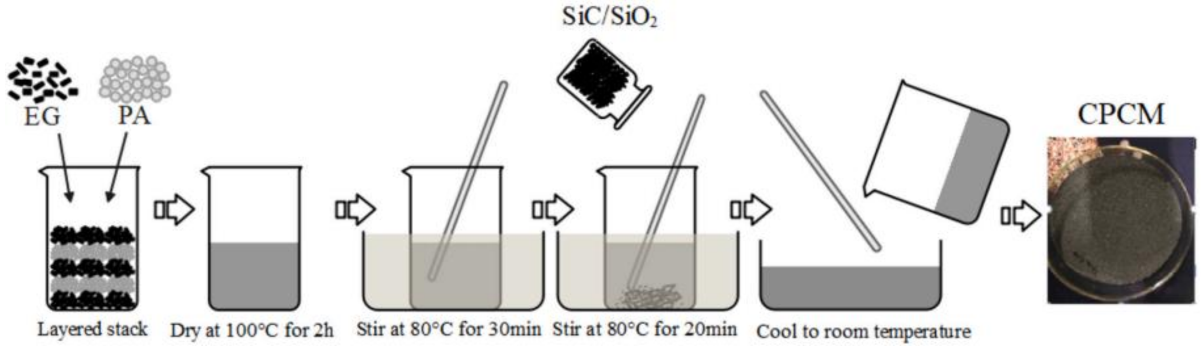

Figure 1. The preparation schematic diagram of composite phase change material [6]

Although the metal oxide-based NePCM shows good chemical stability, the enhancement of its thermal conductivity is relatively mild and thus limited. However, recent studies combining hybrid strategies have shown promising results in addressing this limitation. For instance, the development of composite phase change materials (CPCMs) that combine metal oxide nanoparticles with other nanomaterials has been proven to be effective. Take CPCM-5 containing 10% expanded graphite (EG) and 10% silicon carbide (SiC) as an example. The thermal conductivity of this composite material has been significantly improved, reaching up to 4.086 W/(m·K), which is significantly higher than the lower limit of the thermal conductivity of some pure metal oxy-based ne (0.2383 W/(m·K)).

This enhanced thermal conductivity coefficient, combined with the latent heat of 122.2 J/g, enables CPCM-5 to effectively meet the thermal management requirements of lithium-ion batteries (lib). The experimental results further verified its performance: Under the 2C charging-discharge cycle, the average maximum temperatures of Sanyo LIB and $LiFePO_4$LIB cooled by CPCMC-5 decreased to 39.3°C and 28.6°C respectively, which were reduced by 7.8°C and 3.6°C respectively compared with natural convection. Even under 1C and 2C discharge conditions, the average maximum temperature of Sanyo LIB cooled by CPCM decreased by 1.4°C and 3.9°C respectively, demonstrating superior cooling efficiency.

These findings indicate that by integrating metal oxide nanoparticles with other high-performance nanomaterials such as EG and SiC, the thermal conductivity of NePCM can be significantly enhanced, thereby overcoming the inherent limitation of a slight improvement in thermal conductivity of pure metal oxide-based NePCM. This hybrid method not only enhances the heat dissipation capacity, but also maintains the ideal chemical stability and non-conductivity of the metal oxide-based NePCM, making it more practical in actual LIB thermal management applications.

3.3. Emerging Nanomaterials-Based NePCMs

The emerging NePCM based on nanomaterials, although having excellent performance, had encountered many obstacles in practical applications. For instance, graphene and carbon nanotubes exhibited excellent thermal and electrical conductivity at the nanoscale. However, their large-scale production remained a significant bottleneck. The current synthetic methods, such as chemical vapor deposition and exfoliation techniques, had low yields and high costs. Preparing high-quality graphene with a large surface area and few layers or carbon nanotubes with uniform diameter and length was a complex and time-consuming process. This limited production capacity made it difficult to meet the large-scale demands of the new energy vehicle battery industry, hindering the wide implementation of these materials in battery thermal management systems.

Functionalization and compatibility were also the main challenges faced by emerging nanomaterials. In order to effectively integrate these materials into the PCM matrix, chemical modification of them was usually required. The functionalization process aimed to improve the dispersion of nanomaterials in PCM, enhance their interaction with the matrix, and prevent agglomeration. However, this process was complex and required the use of specific chemicals and reaction conditions. If the functionalization treatment was not handled properly, the emerging nanomaterials might not be well dispersed in the PCM, thereby resulting in inconsistent thermal properties. In addition, the functional groups introduced during the modification process might react with the composition of the battery electrolyte, which might lead to battery degradation over time.

For metal-organic frameworks (MOFs), their stability in the battery environment was a key issue. MOF was composed of metal ions or metal clusters connected by organic ligands, and its structure was usually very sensitive to changes in temperature, humidity and chemical composition. Under harsh working conditions where the temperature of new energy vehicle batteries fluctuated greatly and the electrolyte contained various chemical substances, MOF might undergo structural degradation. This degradation would lead to the loss of its unique pore structure, which was crucial for the storage and transfer of heat. In addition, the mechanical strength of NePCM based on MOF was relatively low, making them prone to damage during battery assembly and operation. Vibration and mechanical shock could cause damage or loss of integrity of the MOF, reduce the effectiveness of the thermal management system, and might affect the overall performance and safety of the battery [7-10]. A novel MOF/NePCM fabrication process was shown on Fig. 2.

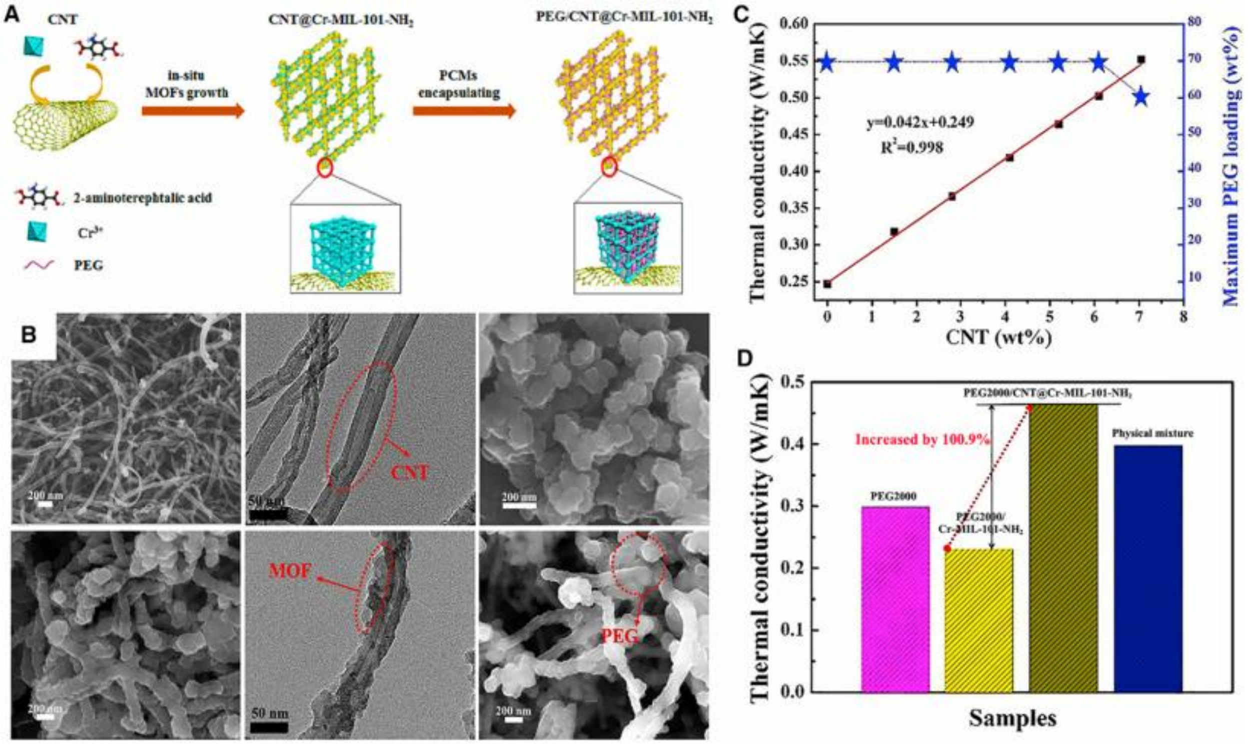

Figure 2. In situ growth MOF enhancement of NePCMs [8]

4. Summary and Suggestions

To address the related issues of metal-based, metal oxide-based and emerging nanomaterium-based NePCM and optimize its application in the thermal management system of new energy vehicle batteries, the following suggestions were put forward.

For metal-based NePCM, in order to alleviate the corrosion problem, surface coating technology should be explored. Coating a thin layer of corrosion-resistant material, such as a polymer or ceramic film, on metal nanoparticles could prevent the metal from coming into direct contact with the battery electrolyte, thereby reducing the risk of oxidation. In terms of cost reduction, research should focus on developing more effective and cost-effective synthetic methods. For instance, exploring solution-based synthetic routes, using cheaper raw materials and simpler equipment, might reduce production costs. To enhance safety, strict quality control during the manufacturing process was a necessary condition to ensure the uniform dispersion of metal nanoparticles in the PCM matrix. In addition, adding insulating barriers or separators around the NePCM of the battery pack could further prevent short circuits.

For metal oxide-based NePCM, efforts should be made to improve its thermal conductivity. This could be achieved by optimizing the size, shape and distribution of metal oxide nanoparticles. For instance, synthesizing nanoparticles with more uniform size and high aspect ratio could increase the contact area between nanoparticles and PCM, thereby promoting better heat transfer. To solve the compatibility problem, appropriate functional group modification on the surface of metal oxide nanoparticles could enhance their interaction with the PCM matrix and promote better dispersion. Furthermore, by simplifying the synthesis and processing steps, such as using a one-step synthesis method, the need for additional surface modification processes was reduced, enabling cost-effective production.

For the emerging NePCM based on nanomaterials, research and development should give priority to improving the large-scale production technology. Collaboration between academia and industry could accelerate the development of more effective synthetic methods for graphene, carbon nanotubes and MOFs. In terms of functionalization and compatibility, it was crucial to develop universal functionalization strategies applicable to different types of emerging nanomaterials and PCM matrices. This could ensure the consistent performance of different battery thermal management systems. In addition, to address the stability issue of MOFs, exploring the synthesis of MOF-based composites with enhanced mechanical and chemical stability, or using MOFs as additives in combination with other more stable materials could improve their applicability in battery environments.

The following table. 1 summarized the advantages and disadvantages of three types of NePCM for a more intuitive comparison:

Table 1. Comparison of various NePCM

Type	advantages	Disadvantages
Metal-Based NePCMs	1. Exceptionally high thermal conductivity 2. Can enhance the mechanical strength of PCM to some extent	1. Prone to corrosion in the battery environment 2. High production cost due to expensive raw materials and complex synthesis processes 3. Potential safety risks of short-circuits
Metal Oxide-Based NePCMs	1. Good chemical stability and thermal resistance 2. Can act as nucleating agents for more uniform phase transitions 3. Non-conductive, suitable for applications requiring electrical insulation	1. Relatively modest improvement in thermal conductivity compared to metal-based counterparts 2. Compatibility issues leading to agglomeration and reduced performance 3. High production cost due to complex synthesis and processing requirements
Emerging Nanomaterials-Based NePCMs	1. Possess unique physical and chemical properties, such as extremely high thermal and electrical conductivity (graphene, carbon nanotubes) 2. Offer potential for innovative functions and performance improvements	1. Difficult to produce in large quantities with high quality 2. Complex and costly functionalization and modification processes for compatibility 3. Stability issues in the battery environment, especially for MOFs

By implementing the proposed suggestions and carefully considering the advantages and disadvantages of each NePCM, a more effective and reliable thermal management solution for new energy vehicle batteries could be developed.

5. Conclusion

This study systematically explored the role of nanocomposite phase change materials (NePCM) in improving the thermal management of new energy vehicle batteries, with a focus on three major categories: metal-based NePCM, metal oxyp-based NePCM, and emerging nanomaterium-based NePCM.

For metal-based NePCM, materials such as copper (Cu) and aluminum (Al) nanoparticles exhibited excellent enhanced thermal conductivity due to their inherent metallic properties, which effectively accelerated thermal diffusion in the phase change matrix. However, severe oxidation at high temperatures and high manufacturing costs posed significant obstacles to practical applications. Surface modification techniques, such as coating polymer layers, held promise in reducing oxidation, but posed challenges in maintaining interfacial thermal contact.

Metal oxyp-based NePCM, including TiO_2 and Al_2O_3, had the advantages of chemical stability, non-toxicity and low cost, and was suitable for long-term thermal regulation. Their relatively low density also reduced the overall weight of the battery pack, which was a key factor in the design of new energy vehicles. However, for high-power battery systems, a moderate improvement in thermal conductivity (typically a 10-20% increase) was insufficient. Therefore, there was an urgent need to develop hybrid strategies, such as combining with carbon-based nanomaterials, to achieve synergistic thermal performance.

Emerging nanomaterials, such as graphene and boron nitride nanosheets, featured unique two-dimensional structures and possessed extraordinary thermal conductivity and high latent heat storage capacity. For instance, graphene-based NePCM could achieve a thermal conductivity enhancement of over 50% at low loads ($\leq$1wt %), while boron nitride nanosheets offered excellent electrical insulation, which was crucial for preventing short circuits in battery modules. However, there were still challenges in scalable synthesis, uniform dispersion, cost-effective production, and the interfacial thermal resistance risk between nanosheets and phase change materials.

In conclusion, NePCM represented a transformative solution for the thermal management of new energy vehicle batteries, balancing heat dissipation efficiency and energy storage capacity. Future research should give priority to interdisciplinary approaches: developing new surface functionalization to enhance the compatibility of nanomaterials and matrices, exploring multi-component hybrid systems to optimize thermoelectric properties, and integrating theoretical simulations (such as molecular dynamics) to guide material design. Solving these problems could not only overcome the current technological limitations but also promote the commercialization of high-performance NePCM, thereby contributing to safer, more efficient and longer-range electric vehicles.

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