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# *Advancements in Nano-Enhanced Coolants for Thermal Management of Electric Vehicle Batteries*

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***Abstract.*** Thermal management of electric vehicle batteries is a major problem that cannot be ignored in the electric vehicle industry. Traditional cooling methods such as air and liquid cooling are no longer able to perfectly handle the heat generated by high-power electric vehicles. Recent studies have shown that nanotechnology can effectively improve the performance of traditional coolants. By dispersing nanoparticles in the base solution, thermal conductivity, specific heat capacity, and interface-driven convective heat transfer can be improved, resulting in better temperature control and reduced temperature gradients within the battery module. In this paper, the mechanisms of nanomaterials to enhance the performance of coolants are systematically reviewed, including thermal transport improvement, high specific surface area effect, and specific heat capacity regulation. Three types of nanomaterials were then analyzed: metals, metal oxides, and carbon-based materials, which show different advantages and use cases in electric vehicle battery thermal management systems. However, despite their good performance in the laboratory, they still face problems such as large-scale production, decentralization stability, and system security in practical applications. All in all, nanotechnology offers important potential for cooling solutions for next-generation electric vehicle batteries, and if breakthroughs in material design and surface engineering can be made in the future, it can complete the leap from the laboratory to the market.

***Keywords:*** Nanofluid, electric vehicle, thermal management, batteries.

## 1. Introduction

With the rapid development of new energy vehicles, the performance of battery thermal management systems (BTMS) has become a key factor affecting the safety, lifespan, and charging efficiency of electric vehicles. Traditional air-cooled and liquid-cooled methods often face the problems of insufficient heat dissipation and poor temperature uniformity when dealing with fast charging and high power density. The introduction of nanotechnology provides a new idea for improving coolant performance. Specifically: dispersing nanoparticles in the base fluid can significantly enhance thermal conductivity, regulate specific heat capacity, and improve convective heat transfer, thereby more effectively inhibiting cell overheating and temperature difference diffusion.

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Current research shows that metals, metal oxides, and carbon-based nanomaterials have shown potential in battery cooling experiments or simulations, but their large-scale applications still face challenges such as stability and safety. Therefore, it is of great significance to systematically explore the mechanism, application and difficulties of nanotechnology in battery cooling to promote the new energy vehicle industry.

## 2. The principles of nanotechnology to improve the cooling effect of coolants

### 2.1. Increase in thermal conductivity

It is attributed to multiple mechanisms. This includes the Brownian motion of nanoparticles, liquid stratification at the solid-liquid interface, and the formation of percolation networks [1]. The enhanced effective energy transfer capability within the fluid is mainly attributed to the promotion of microcirculation by Brownian motion [2]. At the same time, there is a dense liquid layer surrounding the nanoparticles. Thanks to these additional heat conduction pathways, the overall thermal conductivity of the coolant has been improved. At higher concentrations of nanoparticles, these particles interact and form a network like structure. These network like structures act as thermal bridges, further helping to improve the thermal conductivity of the base fluid [3]. It can be found from the combination of these mechanisms that nanofluids indeed have superior thermal conductivity compared to traditional cooling materials.

### 2.2. Higher surface area

Compared to traditional solid additives, nanoparticles exhibit higher surface area and volume ratio, effectively increasing the interfacial area between solid particles and the base fluid. Meanwhile, more places for energy exchange have been created. All of these promote faster heat transfer. For example, needle-like or rod-shaped nanoparticles, which present higher specific surface area than spherical ones, often result in stronger thermal conductivity enhancement [4]. The increased surface area also helps in the development of interfacial liquid layers, which act as additional heat conduction channels. Therefore, the superior heat transfer characteristics of nanofluids are directly linked to the nanoscale dimensions and the high surface area of the dispersed phase.

### 2.3. Specific heat capacity

The effect of nanoparticles on the specific heat capacity of nanofluids remains controversial and strongly dependent on the base fluid. In many water- or glycol-based systems, the addition of nanoparticles tends to decrease the specific heat capacity, which has been explained by the lower heat capacity of solid particles compared to the fluid and by the displacement of high-heat-capacity liquid. On the other hand, several studies on molten-salt-based nanofluids have reported significant increases in specific heat capacity, sometimes exceeding 20–30% with small nanoparticle concentrations [5]. The formation of interface structure, aggregation of nanoparticles, and creation of semi-solid layers for storing external energy all lead to such enhancement. Therefore, it can be concluded that nanoparticles can reduce or increase their specific heat capacity based on the fluid medium and major microscopic interactions.

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## 3. Nanomaterials used in practical applications

### 3.1. Metals

Metal nanoparticles have high solid thermal conductivity and potential thermal network effects, such as silver and copper, making them suitable as working fluids or additives for two-phase devices to enhance the upper limit of heat flux in the evaporation condensation process [6]. Several experiments have shown that silver nanofluids can significantly reduce the thermal resistance of heat pipes and improve the equivalent thermal conductivity [7]. The water copper nanofluid also exhibits lower evaporator temperature and faster thermal response in micro loop heat pipes [8]. Embedding such two-phase devices into battery cooling can reduce the maximum temperature of the cell or limit the spread of thermal runaway under the same heat dissipation conditions. However, metal nanofluids also face practical constraints such as dispersion stability, corrosion, and cost, and require surface modification and anti-corrosion management in engineering.

### 3.2. Metal oxides

Metal oxide nanoparticles are the most commonly used nanoadditives in EV liquid cold plates/microchannels due to their chemical stability, cost, and preparation maturity [9]. $Al_2O_3$, CuO, etc. can improve thermal conductivity and convective heat transfer at low volume fractions, while the penalties for viscosity and pump power are relatively controllable. Research on EV scenarios shows that when using loop heat pipes for battery cooling, liquid-filled CuO-water or $Al_2O_3$-water nanofluids can be used to pressure the evaporator temperature below 60 ℃ under fast charging conditions (about 150 W heat load) [10] press the evaporator temperature below 60 ℃ (radiator 40℃); In the liquid-cold plate/corrugated microchannel, $Al_2O_3$, CuO, and optimized flow direction and flow can reduce the maximum temperature and temperature difference (ΔT) and improve temperature uniformity. The latest values and experiments also provide a trade-off window between ratio, pump power, and pressure drop, providing data support for engineering selection.

### 3.3. Carbon-based nanomaterials

Carbon-based nanomaterials have both ultra-high solid thermal conductivity and high specific surface area, which can significantly improve the equivalent thermal conductivity and convective heat transfer of coolants at low dosing, and are conducive to improving temperature uniformity. Regarding the application of EVs, both graphene nanofluids and graphene functionalized composite phase change materials (PCM) have shown the potential to suppress the peak temperature of battery cells and reduce the ΔT between cells [11]; Graphene nanofluids were used in mixed BTMS (liquid cooling + PCM/porous copper foam) to reduce the average temperature of the battery pack from about 52.2℃ to 47.9℃ [12]. In addition, the performance of nanodiamonds and graphene/Cu hybrid sheets in loop heat pipes can also be transferred to battery scenarios to cope with heat flux peaks during high rate discharge or fast charging. It should be noted that the risk of stable dispersion, surface modification and filter blockage of carbon-based nanofluids must be considered in conjunction with the cooling circuit design.

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## 4. Challenges

### 4.1. Large-scale production

The promotion of nanotechnology in electric vehicle cooling is first limited by large-scale manufacturing and standardization. Particle size and dispersion differences are common phenomena in different batches of nanomaterials, and they are also the reasons for the instability of thermal conductivity and viscosity [13]. At the same time, large-scale preparation requires more energy consumption and surface modification, which leads to higher costs and increased environmental pressure [14]. Introducing indicators such as specific surface area and agglomeration in material characterization, and promoting standardized testing and life cycle assessment are undoubtedly effective solutions.

### 4.2. Stability

Nanofluids are prone to agglomeration and sedimentation in long-term operation, weakening heat transfer properties and increasing pressure drop [15]. Surfactants are often added to maintain dispersibility, but they can cause viscosity increases or performance drift during thermal cycling. Highly thermal conductivity materials such as carbon-based and M-Xene, although significantly improved, are more prone to stacking or aging at high flow rates. Currently, long-term stability data are lacking, so anti-agglomeration surface engineering and online monitoring are key to commercialization [16].

### 4.3. Security

Electrical conductivity, corrosion, and environmental health are the main safety challenges. Metals and other carbon-based nanofluidic materials will greatly improve the conductivity, and if leakage occurs during use, there will be a risk of circuit short circuit [8]. Particles also have corrosion and wear problems on aluminum, copper and other components. On the other hand, the environmental and human safety of nanoparticles still needs to be further evaluated. Studies have recommended prioritizing insulating formulations combined with filtration, sealing, and material compatibility testing to ensure reliable operation of battery cooling systems.

## 5. Conclusion

Focused on the core theme of nanotechnology-enabled thermal management for electric vehicle batteries, this paper studies the application process of nanotechnology from three perspectives. Firstly, the theoretical basis for nanoparticles to improve coolant performance by enhancing heat conduction, high specific surface area and specific heat regulation is summarized. Subsequently, the main used nanomaterials were divided into three categories, and their respective advantages and application cases were studied: Metal nanoparticles have excellent thermal conductivity, metal oxides are more engineering feasible in terms of stability and cost, and carbon-based materials have outstanding performance in temperature homologation due to their ultra-high thermal conductivity and composite capabilities. However, the large-scale production, dispersion stability and system safety of nanotechnology in battery cooling are still bottlenecks restricting its industrialization. Future research needs to form a closed loop in three aspects: material design, system stability, and safety assessment, and promote standardized testing and life cycle evaluation to achieve the reliable implementation of nanocoolants in the thermal management of electric vehicles.

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