# Aluminum Oxide Nanoparticles for Liquid Cooling Systems in Battery Thermal Management

Jason Xie [*]

Oxford International College, Oxford, OX41BD, United Kingdom

* Corresponding Author Email: jason_xie@oxcoll.com

**Abstract.** The increasing power demands and advancements in battery technology have intensified the need for efficient battery thermal management systems (BTMS). Among various cooling methods, liquid cooling is favored for its superior heat capacity, though it faces challenges in thermal conductivity and maintaining temperature uniformity across cells. The incorporation of aluminum oxide nanoparticles into coolants has emerged as a promising solution to enhance heat dissipation in battery packs. Despite the potential benefits, obstacles such as nanoparticle aggregation pose significant barriers to commercialization. This paper explores the feasibility of using aluminum oxide nanoparticles in BTMS by analyzing existing literature and data. Key focus areas include optimizing nanoparticle size and dispersion techniques to mitigate aggregation and improve thermal performance. Additionally, the commercial prospects of this technology are evaluated, considering current market trends and economic viability. This comprehensive review reveals the potential of aluminum oxide nanoparticles to optimize BTMS, paving the way for more efficient and reliable energy storage solutions.

**Keywords:** Battery thermal management system; electric vehicles, aluminum oxide nanoparticles.

## 1. Introduction

Greenhouse gas emissions are a major contributor to climate change and global warming, with transportation being the primary source. In response to these issues, the electric vehicle (EV) market has grown rapidly over the past decade. EVs are expected to play a crucial role in the decarbonization of the transport system. High-voltage batteries are the sole energy source in EVs and are critical for ensuring vehicle efficiency and functionality. Currently, lithium-ion batteries have gained prominence for energy storage of EVs [1].

Despite their advantages, the performance of lithium-ion batteries is limited by operating temperature and voltage [2]. The ideal operational temperature range for these batteries is between 20 to 40 °C. Operating outside this range can negatively impact battery performance and lifespan. To maintain battery cell temperatures within this range, an efficient and reliable battery thermal management system (BTMS) is required. In EVs, thermal management must be meticulously designed to handle heat dissipation under diverse operating conditions and maintain an optimal temperature range within the battery pack. It is also important to provide a homogenous temperature distribution, ensuring the temperature difference between battery cells does not exceed 5 °C, as significant temperature differences could lead to problems like electrical imbalance [3].

An efficient BTMS should manage heat transfer while being cost-effective and compatible with the vehicle's size and mass. Liquid cooling has gained prominence as a method for dissipating heat generated by the battery and maintaining the optimum temperature range due to its high heat capacity. However, liquid cooling systems may be heavier than other cooling systems like air-based systems. Some liquid coolants, such as oils and liquid metals, may also be more viscous and have poor thermal conductivity, requiring higher power for recirculation [3].

The application of nanofluids can notably enhance the thermal efficiency of liquid cooling systems. Al2O3 nanoparticles are popular due to their high thermal conductivity, low material cost, and stability in suspension. However, improving coolant thermal conductivity can result in a rise in required pumping power and poses challenges such as low electrical insulation and potential abrasion and erosion of the microchannels in the cooling system [4].

One solution to these problems is to adjust conditions, particle characteristics, and preparation methods to optimize performance. This research analyses the effect of different conditions on the thermal characteristics and performance of nanoparticles and discusses the feasibility of using aluminum oxide nanoparticles in liquid cooling systems for BTMS from a commercial perspective [5,6].

## 2. Factors Affecting the Thermal Properties of Coolant and Its Performance in the System

Research has found that factors such as base fluid, particle size, volume fraction, preparation methods, pH level, and inlet velocity all affect the thermal conductivity of coolant. Table 1, compiled by Sridhara V et al., illustrates how different factors enhance the thermal conductivity of nanofluids and interact with each other [7].

**Table 1** How these factors affect the thermal conductivity of $Al_2O_3$-based nanofluids [1].

| Author (year) | Base fluid | Concentration | Particle size (nm) | Enhancement ratio | Method/parameters |
|---|---|---|---|---|---|
| Masuda et al. | Water (31.85 °C)<br>Water (46.85 °C)<br>Water (66.85 °C) | 1.3 to 4.3 | 13 | 1.1092 to 1.324<br>1.10 to 1.296<br>1.092 to 1.262 | Two-step method<br>Temperature effect |
| Lee et al. | Water<br>Ethylene | 1.0 to 4.30<br>1.0 to 5.0 | 38.4 | 1.03 to 1.10<br>1.03 to 1.18 | Two-step method |
| Wang et al. | Water<br>Ethylene glycol<br>Engine oil<br>Pump oil | 3.0 to 5.50<br>5.0 to 8.0<br>2.25 to 7.40<br>5.00 to 7.10 | 28 | 1.11 to 1.16<br>1.25 to 1.41<br>1.05 to 1.30<br>1.13 to 1.20 | Two-step method |
| Eastman et al. | Ethylene glycol | 1.00 to 5.00 | 35 | | Two-step method |
| Xie et al. | Water<br>Ethylene glycol<br>Ethylene glycol<br>Ethylene glycol<br>Ethylene glycol<br>Pump oil | 1.80 to 5.00<br>1.80 to 5.00<br>1.80 to 5.00<br>1.80 to 5.00<br>1.80 to 5.00<br>5.00 | 60.4<br>15<br>26<br>60.4<br>302<br>60.4 | 1.07 to 1.21<br>1.06 to 1.17<br>1.06 to 1.18<br>1.10 to 1.30<br>1.08 to 1.25<br>1.39 | Two-step method<br>Solid crystalline<br>Phase effect<br>Morphology effect<br>pH effect |

As shown in Table 1, a maximum enhancement ratio of 1.39 is displayed in a study by Xie. In this study, researchers used 60.4-nm-sized $Al_2O_3$ particles dispersed in water and prepared a stable solution by adjusting the pH. The nanoparticles were de-agglomerated using an ultrasonic disruptor and homogenized with magnetic force agitation. The enhancement observed was 21% for a 5% volume fraction [1].

Not all factors correlate with thermal conductivity enhancement, as seen in Table 1. This paper aims to present a detailed analysis of the factors that do correlate, focusing particularly on the inlet velocity and concentration of nanofluids [1].

### 2.1. Effect of $Al_2O_3$ Nanoparticle Concentration and Inlet Velocity

### 2.1.1 Maximum temperature rise

The discharge rate of an EV refers to the rate at which the vehicle's battery releases its stored energy to power the electric motor and other systems. This rate is typically measured in terms of current (amperes, A) or as a percentage of the battery's capacity over time. The discharge rate is often expressed as a C-rate, which is a dimensionless number representing the rate of discharge relative to the battery's capacity. The 2C discharge rate in Fig. 1 corresponds to the battery discharge in half an hour. The independent factors, inlet velocity and concentration, are examined over a small range (For concentration, ranging from 0.5% to 5%. For inlet velocity, ranging from 0.05m/s to 0.1m/s.) to avoid negative impacts such as pressure drops and particle aggregation [3]. Even slight variations in these parameters can significantly affect thermal properties [5].

Regarding concentration, an inverse relationship is observed in the bar chart from Fig. 1: increasing concentration from 0.5% to 5% reduces the maximum temperature rise. For example, at a 0.5% volume concentration and an inlet velocity of 0.05 m/s, the maximum temperature rise is 12.5 °C, whereas at a 5% concentration and the same inlet velocity, it is 9 °C. Conversely, as inlet velocity increases, the maximum temperature rise decreases.

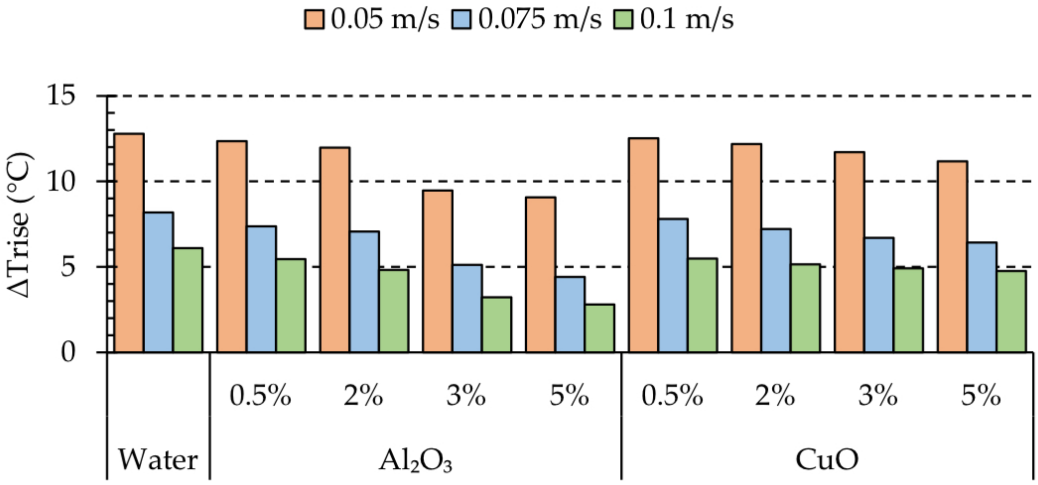

**Fig. 1** How different concentrations of $Al_2O_3$ nanoparticles and inlet velocity affect the Maximum temperature rise of Li-ion batteries [3].

### 2.1.2 Average temperature

Both factors also show an inverse relationship concerning average temperature [8,9]. Peyman Soleymani and his research team compiled Fig. 2, which illustrates how different concentrations of $Al_2O_3$ nanoparticles and inlet velocity affect the average temperature of Li-ion batteries. Similarly, the concentration and inlet velocity were examined over a small range due to the impact of pressure drop and aggregation.

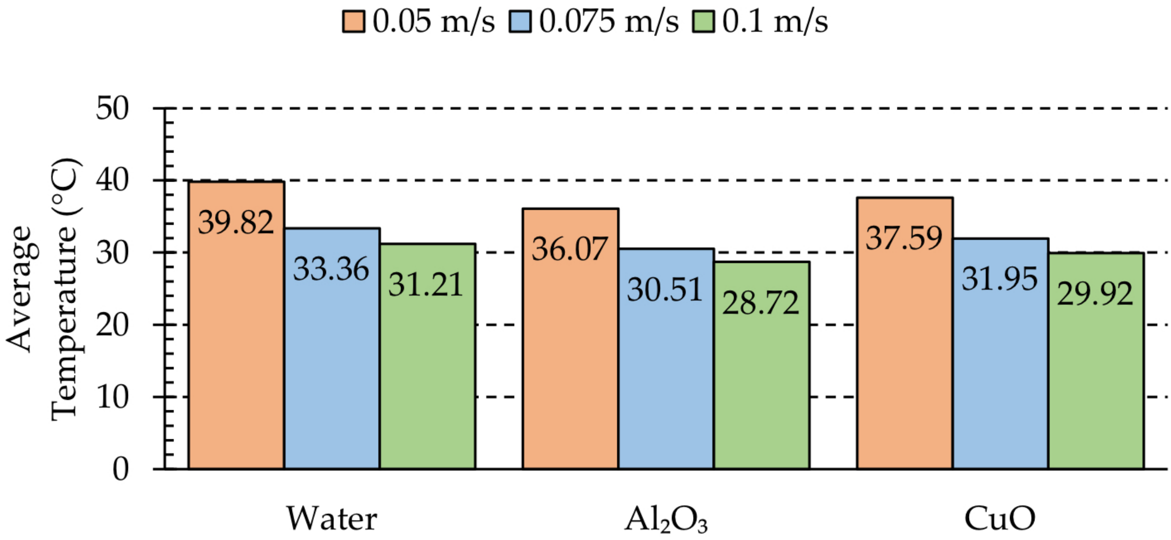

**Fig. 2** Effect of $Al_2O_3$ nanoparticle concentration inlet velocity on the average temperature of the batteries at a 2C discharge rate [3].

These two trends can be explained by the increase in the Nusselt number resulting from changes in volume concentration and inlet velocity. As both volume concentration and inlet velocity increase, the convective heat transfer coefficient also increases. This indicates that convection plays a more significant role than conduction in the coolant, thereby improving the heat transfer efficiency of the cooling system. The primary reasons for the increase in the convective heat transfer coefficient are enhanced thermal conductivity, improved heat capacity, and higher Reynolds numbers [5,6,8].

### 2.2. Temperature Uniformity

Compared to the average temperature reduction, aluminum oxide nanoparticles have a lesser impact on the temperature uniformity of batteries. However, their influence is still significant. $Al_2O_3$ enhances liquid cooling by preventing sharp temperature increases, ensuring that Li-ion batteries remain within a safe temperature range even during prolonged EV operation under high power demand [3].

The maximum temperature reduction typically occurs in the first column of Li-ion batteries, as it receives the initial, most direct contact with the high-velocity coolant flow. In contrast, the batteries at the end of the pack experience the highest temperatures. Additionally, temperature reduction is greater in the center of each battery cell compared to the upper and lower sections due to the higher velocity of the nanofluids at the pack's center relative to the velocity near the walls. Increasing the concentration of aluminum oxide nanoparticles and inlet velocity can reduce the temperature difference between the first column and the rest, highlighting the positive effect of these factors on temperature uniformity when using $Al_2O_3$ nanoparticles [3].

## 3. Negative Effect of Inlet Velocity and Al2O3 Nanoparticle Concentration

### 3.1. Pressure Drop

Increasing inlet velocity and concentration can significantly improve the system's heat transfer efficiency but also introduces challenges. A key concern is the rise in pressure drop, which reduces the pump's effective pressure. This increase in pressure drop within the channels can lead to higher power consumption by the pump [3]. Typically, higher pressure drops require a larger pump, resulting in greater pumping power usage. Moreover, when the inlet velocity in the channels is low, the pressure drop across the batteries can be considerably higher than in the channel flow, which may be problematic. However, the advantages of enhanced heat transfer generally outweigh the minor drawbacks of increased pumping power, provided that optimal values for concentration and inlet velocity are achieved [4].

### 3.2. Aggregation of Nanoparticles

Nanoparticles often struggle to remain stable in the base fluid. Unstable nanoparticles tend to agglomerate, aggregate, and form clusters, leading to separation from the base fluid and sedimentation [4]. If fluid velocities are too low, the number of clustered particles increases, resulting in poor heat transfer. Higher velocities reduce the likelihood of clustering, thereby improving heat transfer. Similarly, high nanoparticle concentrations increase the likelihood of clustering as particles are closer together. Conversely, low concentrations lead to insufficient thermal conductivity of the base fluid, resulting in inefficient heat transfer and difficulty maintaining the battery's ideal operational temperature range of 25 to 40 degrees Celsius [3]. Therefore, an optimum value for the nanoparticle concentration and inlet velocity is required to balance out both sides.

### 3.3. Abrasion and Erosion of Nanoparticles to Microchannels

Nanofluids contain nano-sized solid particles. The flow of these particles can cause damage to the pumping microchannels through erosion and abrasion. As nanoparticles circulate with the coolant, they collide with the microchannel surfaces. Over time, this can lead to wear on the microchannels. Additionally, the conductivity of nanoparticles may adversely affect the performance of liquid cooling systems. Therefore, erosion and corrosion significantly impact the long-term, stable functioning of nanofluids in industrial applications [4].

## 4. Looking Forward Perspectives

### 4.1. Future Market Perspective

$Al_2O_3$ nanoparticles stand out as competitive nanoparticles used in the liquid cooling system of BTMS due to the following factors. The market price of aluminum oxide nanoparticles makes them a cost-effective alternative to more expensive materials used in BTMS. $Al_2O_3$ nanoparticles are typically priced between \$50 and \$100 per kilogram, thanks to the abundance of aluminum, mature production technology, and large-scale manufacturing capabilities. These factors make them competitive with advanced materials such as silicon carbide (SiC), carbon nanotubes (CNTs), and graphene. For example, SiC nanoparticles, while offering excellent thermal properties, cost between \$200 and \$500 per kilogram, mainly due to more complex production processes and raw material costs. Similarly, despite their excellent thermal and electrical conductivity, CNTs and graphene are prohibitively expensive, costing up to \$1,000 and \$5,000 per kilogram, respectively. This significant price difference highlights the advantages of aluminum oxide in applications where cost-effectiveness is critical.

From the literature review, the incorporation of aluminum oxide nanoparticles into the cooling system significantly enhances thermal transfer with the adjustment of factors affecting the thermal properties of batteries, leading to prolonged battery life and improved energy efficiency, which, in turn, reduces operational costs. The high cost-performance ratio of aluminum oxide nanoparticles highlights its economic viability for BTMS, especially in the automotive industry, where large-scale adoption depends on cost control. While other nanoparticles may have superior thermal properties, the combination of sufficient thermal enhancement and significantly reduced cost makes alumina an attractive option for widespread use in EVs. In addition, the mature supply chain and scalability of alumina production further enhance its viability, allowing manufacturers to meet the growing demand for efficient thermal management solutions without incurring the prohibitive costs of high-performance alternatives.

Governments are increasingly prioritizing the safety and environmental impact of EVs. $Al_2O_3$ nanoparticles are particularly favorable in this regulatory context due to their non-toxicity, recyclability, and minimal impact on ecosystems, making them superior to other potential nanofluids for liquid coolants. In some countries, such as China, governments support the adoption of these advanced materials through economic incentives like tax reductions and subsidies for R&D.

Going forward, alumina prices are expected to remain stable, supported by economies of scale and increased production capacity. As demand for BTMS continues to rise in EVs, alumina nanoparticles are expected to capture a significant market share, balancing performance and affordability in line with the industry's pursuit of cost-effective and sustainable solutions.

## 4.2. Challenges or Commercialisation and Future Research Directions

Increasing the inlet velocity and $Al_2O_3$ nanoparticle concentration can lead to a rise in pressure drop, which brings several economic disadvantages. The higher pumping power consumption demands more energy to operate the system and leads to more frequent maintenance due to the increased load on the pumps, thereby raising operational costs. Additionally, a larger pump may be required, which takes up more space in EVs and necessitates a more complex design for integration, further adding to costs. However, the $Al_2O_3$ nanoparticle concentration is kept relatively low to prevent particle aggregation, ensuring that the rise in pressure drop does not significantly outweigh the benefits of enhanced thermal conductivity in the fluid.

In this context, $Al_2O_3$ nanoparticles may be less competitive compared to other nanoparticles, such as CuO, which has a relatively smaller impact on pressure drop and is thus more commercially attractive. However, by varying factors such as viscosity and concentration, $Al_2O_3$ nanoparticles may still offer superior heat transfer performance, potentially outweighing the disadvantages associated with increased pressure drop. Future research should focus on identifying the optimal nanofluids, conditions and designs that achieve the best balance between thermal performance and pressure drop. Advanced system designs, including optimized microchannel geometries, should be further investigated to minimize frictional losses caused by the viscosity of nanofluids and internal fluid friction between layers moving at different velocities.

The theory explaining agglomeration is electrostatic stabilization. According to this theory, if the Van Der Waals attraction force between nanoparticles exceeds the electric double-layer repulsive force (EDRF), collisions occur [4]. During these collisions, nanoparticles agglomerate and form clusters, which can settle due to gravity, deteriorating the thermal and rheological properties of the nanofluid and potentially causing blockages in microchannels [4]. As a result, long-term stability is compromised, leading to several technical and economic challenges. The enhancement in thermal transfer efficiency provided by $Al_2O_3$ nanoparticles becomes less effective as the nanoparticles aggregate, reducing the thermal conductivity of the nanofluid. This inefficiency increases energy consumption to maintain optimal battery temperatures. Additionally, frequent maintenance is required to address blockages and fouling within the cooling channels, which is economically detrimental. The reduced thermal transfer efficiency also fails to adequately protect the batteries, shortening their lifespan and undermining the primary objective of using aluminum oxide nanoparticles in the cooling system.

Researchers have found that auxiliary techniques used in nanoparticle preparation can significantly improve nanofluid stability. One widely used physical dispersion technique is ultrasonic action, which includes methods like water bath ultrasonic vibration and probe ultrasonic vibration. This approach effectively breaks up particle clusters and reduces particle size. Key factors influencing nanofluid stability include temperature, concentration, pH, and particle size. Therefore, future research should prioritize analyzing these factors to enhance stability further [10].

In addition to aggregation, erosion and abrasion of the system's microchannels must be taken seriously. Understanding how these processes occur is crucial. As nanoparticles circulate with the coolant, they collide with the microchannel surfaces, leading to gradual wear. This wear can eventually cause leakage of the nanofluids, posing serious safety risks. Moreover, the conductivity of the nanoparticles may negatively impact the performance of liquid cooling systems. Erosion and corrosion thus significantly affect the long-term stability and functionality of nanofluids in liquid cooling systems. The associated maintenance costs for channel repair and nanofluid replenishment further diminish the appeal of these systems for large-scale industrial use.

Owing to the fact that erosion and abrasion to the microchannel is a much less important problem compared to other issues like aggregation and pressure drop, there is a lack of experimental investigations focusing on the factors that affect the wear and corrosion of nanoparticles on the surface of electronic devices in order to find ways to avoid or mitigate wear and corrosion and find the best nanofluids.

## 5. Conclusion

The use of $Al_2O_3$ nanoparticles can significantly enhance the thermal transfer efficiency of liquid cooling systems in BTMS or lithium-ion batteries, helping to maintain the battery's operational temperature within the optimal range. Additionally, $Al_2O_3$ nanoparticles improve temperature uniformity across the battery, although this effect is limited. The enhancement of thermal conductivity in liquid cooling systems depends significantly on the conditions, particle characteristics, and preparation methods. Optimizing these factors is crucial not only for improving thermal efficiency but also for mitigating challenges such as particle aggregation, erosion, abrasion of microchannels, and pressure limitations. Despite potential development costs associated with scaling up the use of $Al_2O_3$ for large-scale production, the high cost-performance ratio, abundant availability, stability of alumina production, straightforward material preparation methods, and environmental friendliness of $Al_2O_3$ nanoparticles make them a promising candidate for market share and commercial viability in liquid cooling systems for BTMS. Furthermore, improved BTMS can contribute to overall cost reductions in EV production, making EVs more affordable and appealing to consumers. This, in turn, can drive further growth in the EV market, creating a positive feedback loop that supports the adoption of aluminum oxide nanoparticles.

## References

[1] Sridhara Veeranna and Satapathy Lakshmi Narayan. Al2O3-based nanofluids: a review. Nanoscale Research Letters, 2011, 6: 456.

[2] Kumar Pradeep, Chaudhary Deepak, Varshney Peeyush, et al. Critical review on battery thermal management and role of nanomaterial in heat transfer enhancement for electrical vehicle application. Journal of Energy Storage, 2020, 32: 102003.

[3] Soleymani Peyman, Saffarifard Ehsan, Jahanpanah Jalal, et al. Enhancement of an air-cooled battery thermal management system using liquid cooling with CuO and Al2O3 nanofluids under steady-state and transient conditions. Fluids, 2023, 8(10): 261.

[4] Sun Le, Geng Jiafeng, Dong Kaijun, et al. The applications and challenges of nanofluids as coolants in data centers: A review. Energies, 2024, 17(13): 3151.

[5] Usri N. A., Azmi W. H., Mamat R., et al. Thermal conductivity enhancement of Al2O3 nanofluid in ethylene glycol and water mixture. Energy Procedia, 2015, 79: 397-402.

[6] Kong Minsuk and Lee Seungro. Performance evaluation of Al2O3 nanofluid as an enhanced heat transfer fluid. Advances in Mechanical Engineering, 2020, 12(8): 1687814020952277.

[7] Kole Madhusree and Dey T. K. Thermal conductivity and viscosity of Al2O3 nanofluid based on car engine coolant. Journal of Physics D: Applied Physics, 2010, 43(31): 315501.

[8] Zhou Sheng-Qi and Ni Rui. Measurement of the specific heat capacity of water-based Al2O3 nanofluid. Applied Physics Letters, 2008, 92(9): 093123.

[9] Yetik Ozge and Karakoc Tahir Hikmet. A study on lithium-ion battery thermal management system with Al2O3 nanofluids. International Journal of Energy Research, 2022, 46(8): 10930-10941.

[10] Tao Qi, Zhong Fei, Deng Yadong, et al. A review of nanofluids as coolants for thermal management systems in fuel cell vehicles. Nanomaterials, 2023, 13(21): 2861.