Enhancing Liquid Cooling Systems in Electric Vehicle Batteries: Principles and Nanomaterial Innovations

Zeyi Zheng*

Department of Chemistry, University College London, London, WC1H 0AJ, United Kingdom

*Corresponding author: zeyi.zheng.22@ucl.ac.uk

Abstract. As electric vehicles (EVs) continue to grow in popularity, managing the thermal behavior of lithium-ion batteries (LIB) has become increasingly important. Higher energy densities in batteries lead to significant heat generation during operation, which can cause short circuits, fires, and overall performance degradation. To maintain safety and performance, liquid cooling systems play a crucial role in controlling battery temperatures. This paper explores the principles behind liquid cooling systems used in EV batteries and discusses recent methods to enhance their efficiency. Special focus is given to the integration of nanomaterials, such as metal oxides, graphene, and carbon nanotubes, into base coolants to form nanofluids. These nanomaterials, known for their high thermal conductivity and large surface area, improve the thermal properties of the coolant, facilitating better heat absorption and dissipation. By using nanofluids, the cooling performance can be significantly enhanced, reducing the risk of localized overheating and ensuring safer, more efficient battery operation.

Keywords: Liquid coolants; nanofluids; graphene; electric vehicle.

1. Introduction

With the improvement of people's environmental awareness and the rise of traditional fossil fuels' prices, the global sales of EVs have increased significantly these years, and more people have chosen to buy EVs, and this trend has continued. Fig. 1 shows the US EV sales database from 2021 to 2024 and the forecast of EV sales and growth from 2024 to 2030 [1]. Compared with 2021, the sales volume of EVs in the first half of 2024 increased by one million, with a percentage of about 66%, reaching a record-breaking 1.5 million.

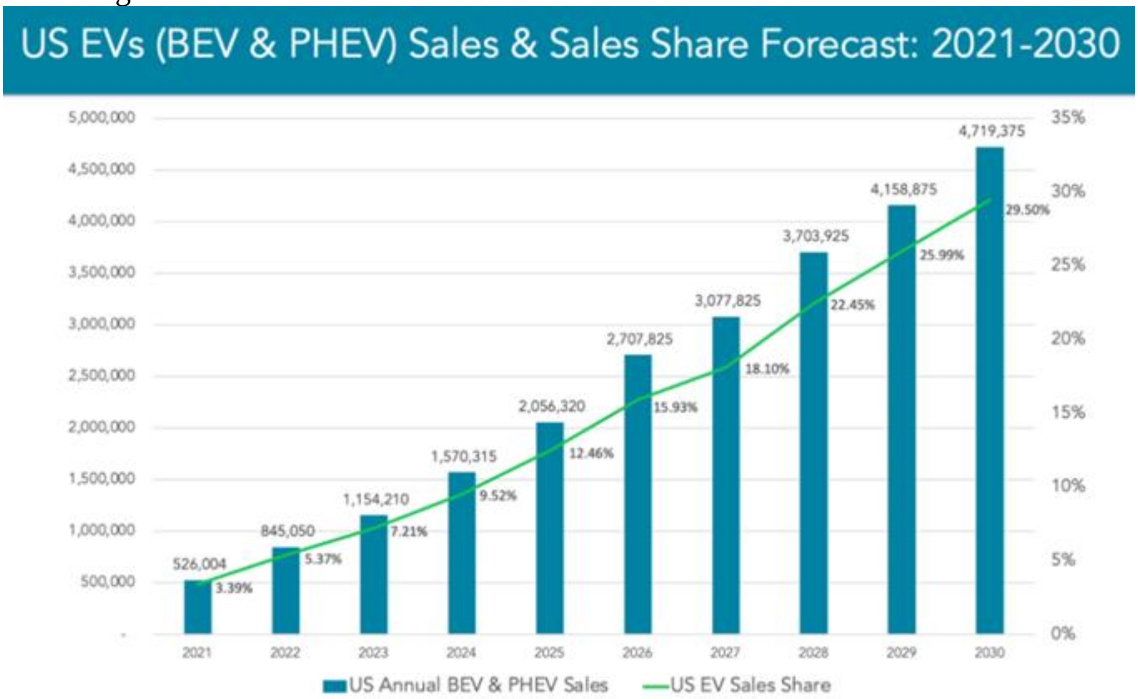

Fig. 1 US EV sales data and forecast from 2021 to 2030 (2024 data) [1].

Battery safety will face more difficulties due to the increased need for EV battery systems with higher energy densities, quicker charging speeds, and more power. According to Fig. 2 below, LIBs are mainly composed of cathode, anode, separator, and electrolyte. When it is running, the electrode will generate heat, and exceeding a certain temperature will lead to thermal runaway, resulting in a short circuit and fire [2].

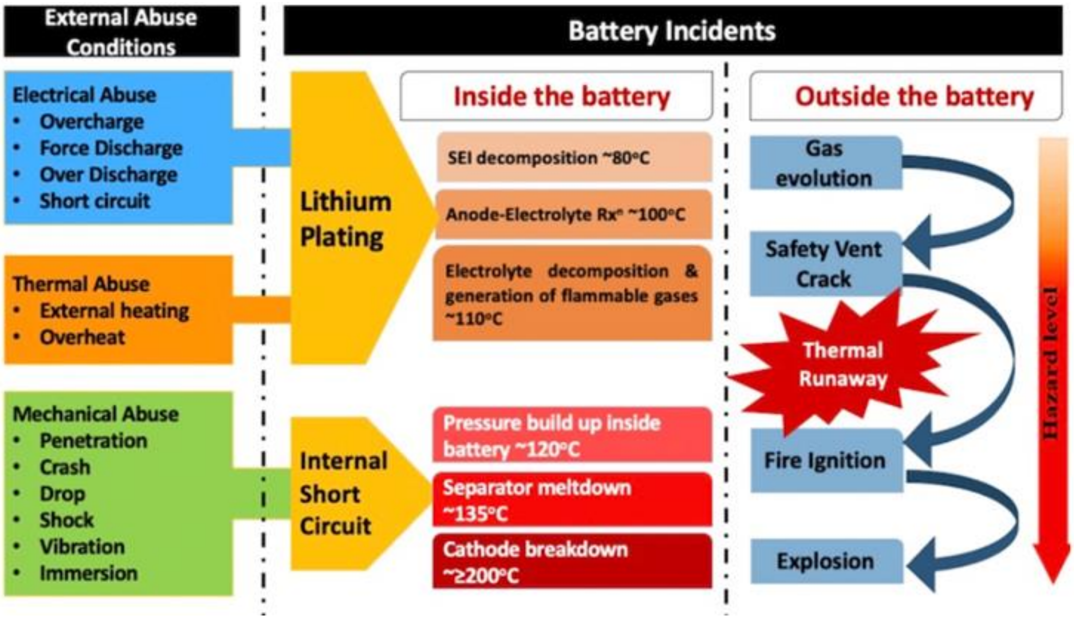

Fig. 2 Battery abuse conditions [2]

Thermal runaway and the presence of flammable components are the causes of fires and explosions in LIBs. The most effective method of heat dissipation is to protect the battery from heat damage by improving the battery's outer shell and adding coolant. Needed safety standards can be met with an effective Battery Management System (BTM) and a well-designed battery pack [3]. This paper is going to discuss the improvement of BTMs containing nanotechnology in EVs and their limitations.

2. Battery Safety Improvement and BTMs

2.1. Battery Optimal Temperature Range

To improve these properties, Nanotech is needed. It can offer both batteries and car components materials. For example, changing anode and cathode nanomaterials and adding BTMs in EVs. BTMs can control the temperature of the battery and minimize the formation of small-scale hot zones [3]. Depending on the method of heat transfer, typical BTMs are divided into traditional air-cooling systems, liquid cooling systems, phase-change materials (PCMs), and liquid coolants containing water and glycol are discussed.

LIBs cannot work effectively at extremely high or very low temperatures, and under adverse working conditions, so thermal control is required within their operating temperature range to maintain their long-term operation and vehicle performance. As Fig. 3 below shows, the battery's optimal temperature range is between 15 degrees centigrade to 35 centigrade [4].

The uniformity of the temperature range and temperature distribution within the battery pack is important, which will affect the normal charging and discharging speed of the battery.

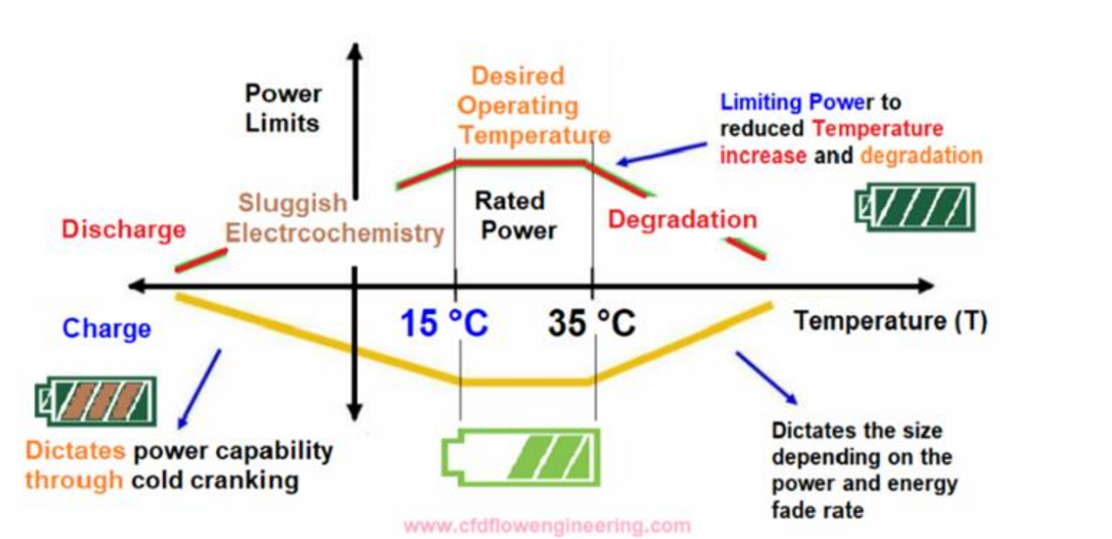

Fig. 3 Effect of temperature on battery's life [4]

2.2. The Principle of the Liquid Cooling System

Coolant must be utilized for the battery to operate safely and correctly [5]. Air cooling systems and paraffin-free PCMs have lower thermal conductivity than liquid coolants. In areas with high ambient temperatures, avoid using this procedure. PCMs typically work with other cooling systems. Additionally, the specific heat and heat transfer coefficient of liquid coolant is high. Indirect cooling is a feature used by a few electric vehicle manufacturers, including Tesla and General Motors [4]. An air heat exchanger that passes through the battery cells of an electric vehicle uses a liquid to cool the batteries. This device uses forced airflow, or convection, to transfer heat from a liquid into the air. Glycol and water are combined to create the coolant [5].

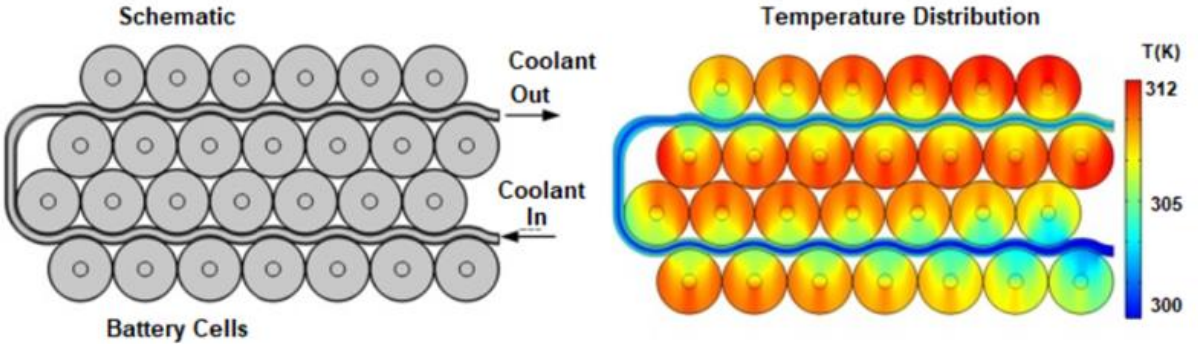

Fig. 4 Liquid cooling system for battery [4]

The use of cold plates between each prismatic cell was demonstrated in Fig. 4 above by General Motors. The microchannels present on the cold plates are designed to remove convective heat from the batteries. Between cylindrical cells, Tesla has employed wavy tubes [4]. To fill the gaps between the battery cells and cooling ducts, thermally conductive and electrically insulated material is applied.

As Fig. 5 above shows, the Liquid cooling of batteries is shown and is circulated through channels built within or around the battery pack [4]. The coolants absorb heat from battery cells and transfer it to the heat exchanger or radiator. Then, the heat is dissipated.

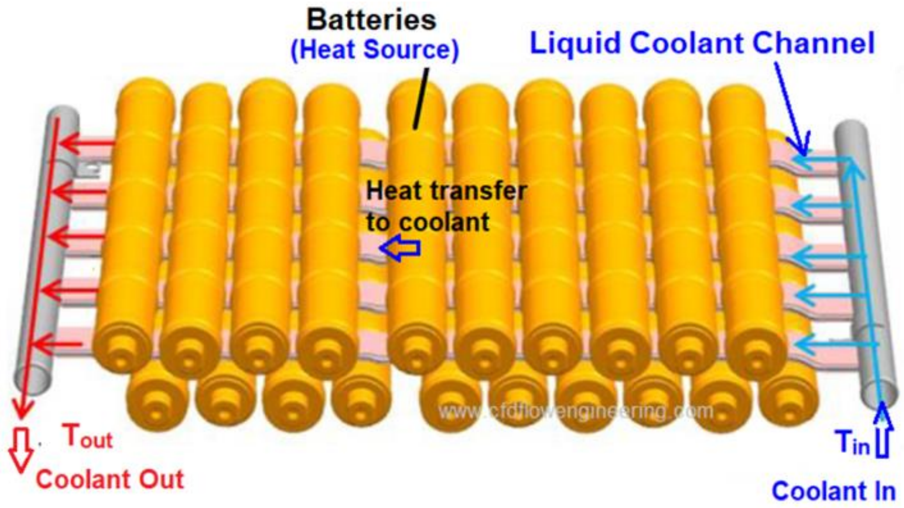

Fig. 5 Liquid coolant for battery [4]

2.2.1 Tesla liquid cooling systems

Tesla's battery's cooling system includes a pump, expansion box and heat exchanger. The coolant circulates through the battery under the action of the pump, reducing the heat in the battery. The glycol circulating in the pipe will take away the heat generated by the battery during the charging and discharging operation. When the glycol flows through a radiator on the outside of the battery, heat is released into the environment [6]. The glycol is transferred through an external radiator, releasing its heat into the surrounding air. Tesla regulated a cell module's temperature distribution using a serpentine-channel cooling plate [7]. It is found that the arrangement of the serpentine channel can enhance the heat transfer capacity of the cooling plate. Its thermal management performance is superior to standard parallel channel liquid cooling plates (LCP). The cooling plate was used by Tesla as a basis for a BTM method.

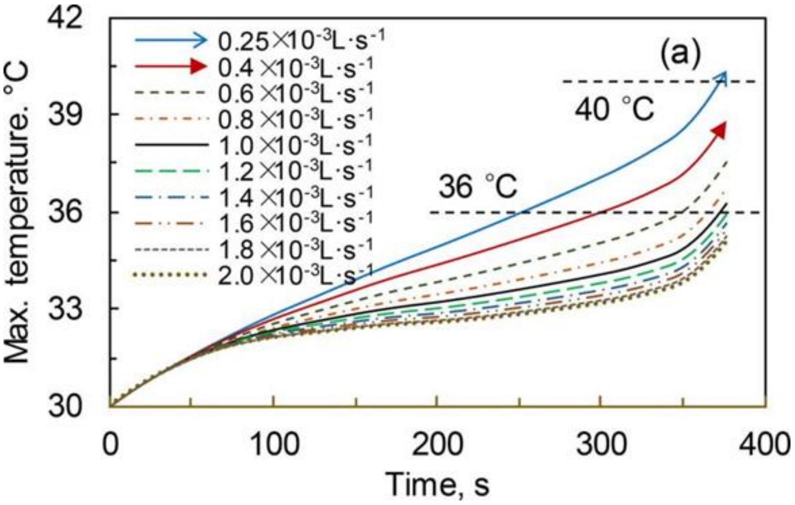

Fig. 6 The relationship between the temperature increases of cell modules and the rate of fluid flow [6]

Fig. 6 shows the relationship between the temperature of the battery module and the flow rate of the liquid in the channel. The maximum temperature will decrease when the flow rate of the channel and liquid in the battery module increases [7]. When a LIB cell was thermally managed using a heated silicon plate, it was found that the number of channels and the liquid flow velocity had a significant impact on the temperature distribution of the cell. It was also less logical in terms of flow direction based on the technique of liquid cooling.

2.3. Nanoparticles in Liquid Coolant

High-heat-producing electronic chips require cooling that standard cooling methods and common liquid coolants do not adequately meet. As a result, high-efficiency electronic devices require new approaches and coolants with great thermal performance to dissipate their generated heat to achieve expected efficiency and reliability [8].

2.3.1 Alumina (Al2O3)

Liquid coolants also have some disadvantages. They will increase the weight and cost of vehicles and have low thermal conductivity like traditional air-cooling systems and PCMs [9]. Nanomaterials like alumina (Al_2O_3) are used to increase the thermal conductivity. SEM image shows the nanoparticles have a loose microstructure with wide dispersion stability on the given surface. The size of nanoparticles selected was found to be in the range of 36 to 42 nanometers, which will have high heat transfer surface area and thermal conductivity. Alumina nanoparticles have a crystal structure. (Fig. 7).

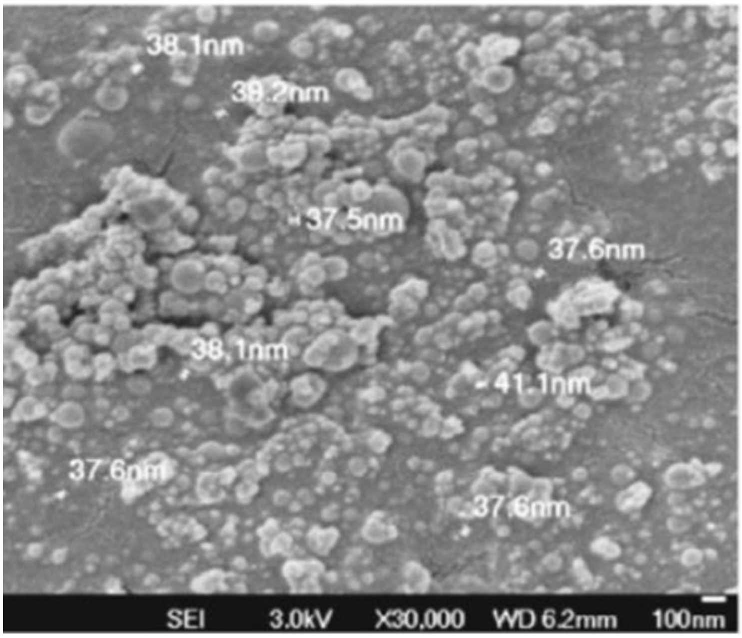

Fig. 7 SEM of pure Al_2O_3 [7]

In alumina's specific performance in water-based liquid coolants, the difference in thermal conductivity to the concentration of nanoparticles and temperature is in Table 1 and Fig. 8. After adding Al_2O_3 to water, thermal conductivity was found to increase on a linear trend. In the concentration of 0.1 % alumina, thermal conductivity is between 0.679 and 0.712 watts per meter Kelvin from 25 degrees centigrade [7]. In the concentration of 0.6 % of Al_2O_3, thermal conductivity increases to 0.711 watts per meter Kelvin at ambient temperature and 0.752 watts per meter Kelvin at 65 degrees per meter Kelvin.

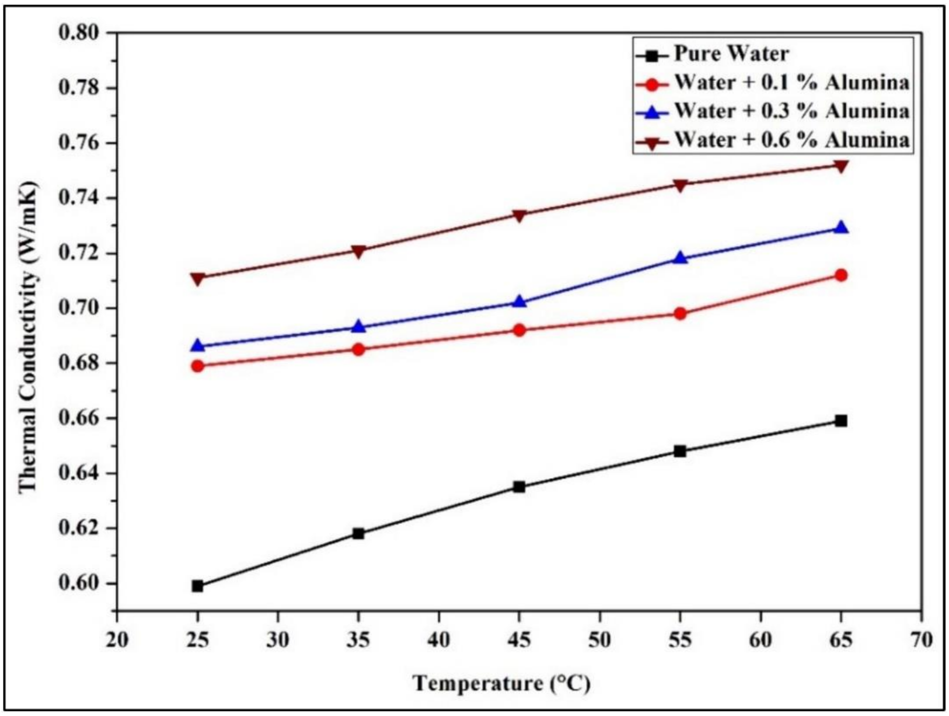

Fig. 8 Thermal conductivity variations of alumina-enhanced water [7]

Table 1 Thermal conductivity of water and nanofluids to temperature [7]

Temperature (°C)	Thermal conductivity (W/mK)			
	Water	Water+0.1% Al_2O_3	Water+0.3% Al_2O_3	Water+0.6% Al_2O_3
25	0.599	0.679	0.686	0.711
35	0.618	0.685	0.683	0.721
45	0.635	0.692	0.702	0.734
55	0.648	0.698	0.718	0.745
65	0.659	0.712	0.729	0.752

2.3.2 Graphene

Graphene is a two-dimensional substance made up of a single layer of hexagonally organized carbon atoms. Its superior thermal, mechanical, and electrical qualities offer a number of potential benefits when combined with liquid coolants. Its thermal conductivity is high [10]. Because of their superior inherent properties, graphene derivatives are intriguing nanomaterials to produce nanofluids. Viscosity and rheological behavior in a broader sense are important characteristics of thermophysical profiles, in addition to thermal properties, to assess the potential of graphene-based nanofluids as dependable and efficient heat transfer fluids [11]. Graphene spread in a base liquid, like water, oil, or glycol, can greatly increase the fluid's thermal conductivity. Because of their improved heat transfer properties, the resultant nanofluids—which are suspensions of graphene nanoparticles in base fluids. It is suited for cooling applications in industrial, automotive, and electrical systems. The coolant's heat transfer coefficient may be raised by adding graphene. This is crucial for devices that need high-performance electronics for effective heat dissipation, like cooling systems, radiators, and heat exchangers. Because of graphene's high specific surface area, even a small amount of it [10].

3. Limitations of Adding Nanofluid

3.1. Al_2O_3 Nanoparticles Blocking the Coolant Tubes

Due to the Van der Waals force and the lack of stability of coolant particles, Al_2O_3 nanoparticles tend to aggregate into clusters in liquid coolant. When these nanoparticles accumulate, they can block the channels in the coolant system that allow the liquid to pass through, restricting the flow of the liquid and resulting in low thermal conductivity and overheating of the battery system. Even if the tube is not completely blocked, the accumulation of nanoparticles reduces the surface area within the tube that can be used for heat transfer [11]. The reason nanoparticles enhance heat conduction is that they have a high specific surface area, which is also reduced when they aggregate. This will make the liquid coolant system with Al_2O_3 need frequent maintenance, increasing the cost of battery operation.

3.2. Maintenance Challenges

Given changes in viscosity, thermal properties, and potential settling problems, cooling systems may need to be modified or specifically designed to accommodate nanofluids. This increases the complexity of system design and maintenance. Maintaining a system using nanofluids can be more challenging because of the need to regularly monitor fluid stability, remove potential deposits, and ensure that system components are not eroded or corroded.

4. Conclusion

In conclusion, according to this paper, as the demand for EVs continues to grow, ensuring the safety of LIBs through effective thermal management is critical. Liquid cooling systems, especially those enhanced with nanomaterials, offer a promising solution to the challenges posed by high-energy-density batteries. By maintaining an optimal operating temperature range and preventing thermal runaway, these systems help improve the safety and reliability of EVs, making them a viable option for widespread adoption in the future. Further development of nanofluids technology will continue to improve the performance and safety of EVs, paving the way for more sustainable transportation systems.

References

[1] Admin. EV Sales 2024. August 4, 2023. Retrieved on September 13, 2024. Retrieved from: https://aubreeqnatasha.pages.dev/dzidqc-ev-sales-2024-nwzjyy/

[2] Lithium-ion battery safety - perils and promises • EVreporter. October 27, 2021. Retrieved on September 13, 2024. Retrieved from: https://evreporter.com/lithium-ion-battery-safety-perils-and-promises/

[3] BEVs and PHEVs Thermal Runaway Sensor Solutions, CO2 Sensors. 2023. Retrieved on September 13, 2024. Retrieved from: https://en.gassensor.com.cn/ThermalRunawaySolutions/index.html

[4] Sharad Pachpute. Battery Cooling Techniques in Electric Vehicle · CFD Flow Engineering. November 7, 2021. Retrieved on September 13, 2024. Retrieved from: https://cfdflowengineering.com/battery-cooling-techniques-in-electric-vehicle/#google_vignette

[5] Meyer, E. Tesla Batteries Cooling and Heating: How The Battery Is Kept Cool. March 19, 2024. Retrieved on September 3, 2024. Retrieved from: https://www.evspeedy.com/tesla-batteries-cooling-heating/#:~:text=The%20liquid%20cooling%20system%20in%20Tesla%20is%20a

[6] Sheng Lei, Su Lin, Zhang Hua, et al. Numerical investigation on a lithium ion battery thermal management utilizing a serpentine-channel liquid cooling plate exchanger. International Journal of Heat and Mass Transfer, 2019, 141: 658–668.

[7] Roy Abin, Venkitaraj K. P., Vigneshwaran Pethurajan, et al. Enhanced convective heat transfer with Al2O3-water nanofluid in a PCM-based thermal energy storage system. Journal of Energy Storage, 2024, 97: 112853.

[8] Cho Ching-Chang, Yau Her-Terng and Chen Cha’o-Kuang. Enhancement of natural convection heat transfer in a U-shaped cavity filled with Al2O3-water nanofluid. Thermal Science, 2012, 16(5): 1317-1323.

[9] Ho Ching-Jenq, Huang J. B., Tsai P. S., et al. Water-based suspensions of Al2O3 nanoparticles and MEPCM particles on convection effectiveness in a circular tube. International Journal of Thermal Sciences, 2021, 50(5): 736-748.

[10] Rasheed Abdul Khaliq, Khalid M., Rashmi W., et al. Graphene based nanofluids and nanolubricants–Review of recent developments. Renewable and Sustainable Energy Reviews, 2016, 63: 346-362.

[11] Suresh K., Selvakumar P., Kumaresan G., et al. A critical review on the effect of morphology, stability, and thermophysical properties of graphene nanoparticles in nanolubricants and nanofluids. Journal of Thermal Analysis and Calorimetry, 2022, 148(2): 451-472.