

A Review of Liquid Cooling for Electric Vehicle Thermal Management

Zhihua Shao^{1, a}

¹Beijing National Day School, Beijing, 100039, China

^aJasmineSZH@hotmail.com

Abstract: As global automotive industries undergo a massive transition toward New Energy Vehicles (NEVs), maintaining the suitable temperature for the increasing compact and high- power electric motors has become a significant challenge. This review of literature systematically reviews the history, current state, and future path of development of liquid cooling technologies for electric vehicle (EV) thermal management. By comparing traditional air cooling with advanced liquid cooling — including the innovative application of hybrid nanofluids, direct liquid cooling, and micro pump integration— this review highlights the thermal performance and efficiency contributed by liquid systems. In electric motors, increased winding temperature raises copper losses (I^2R), reducing motor efficiency. This applies directly to the motors used in electric vehicles, which further emphasizes the need for advanced cooling methods. This essay also addresses the challenges associated with liquid cooling, specifically regarding the complexity of structure, the expensive costs, and the long- term stability of advanced coolants. By synthesizing recent international and domestic research, this review presents a framework for optimizing thermal management efficiency and proposes directions for future research.

Keywords: Electric motors, Electric vehicles, Liquid cooling, Thermal management.

1. Introduction

1.1. The Shift to New Energy Vehicles and the Thermal Challenge

As we move further into the decade and approach 2026, the global automotive transition to New Energy Vehicles (NEVs) has reached a critical transition point. Central to this transition is the electric motor in a NEV. However, as these electric motors become increasingly smaller, more compact, and significantly more powerful, the amount of heat they generate during operation also increases. This increasing heat generation makes the cooling system for NEV electric motors ever more critical for maintaining a suitable and stable temperature. Without such temperature regulation, the motor cannot function properly or efficiently.

As mentioned in the abstract, increased temperature would lead to the exhaust of the copper and iron incorporated in the motor, which affects the efficiency. Therefore, temperature regulation is essential about preserving the electrical efficiency of the vehicle's electric motor.

1.2. The Significance of Liquid Cooling

Historically, electric motors relied heavily on traditional air cooling systems to lower temperatures, prevent overheating, and avoid decrease in operational efficiency. However, the limitations of air cooling have become increasingly apparent under the presence of modern high power density EV motors. Consequently, liquid cooling has now emerged as the dominant and most commonly used method for cooling in electric vehicle motors.

The significance of reviewing and advancing liquid cooling technology is prominent. It is essential for increasing the efficiency of the cooling process itself, which in turn leads directly to increased efficiency of the electric motor. Furthermore, the optimization of these systems also

contributes to the improvement of environmental performance. For example, the European Union's updated carbon neutrality goals, specifically, the Commission Regulation (EU) 2019/1781 of 1 October 2019; China's 2026 "Green and Efficiency" industrial protocols, "Minimum allowable values of energy efficiency and values of efficiency grades for motors" (official code number: GB 18613-2020), both demand higher motor energy efficiency. If liquid cooling technologies can be further improved, the overall efficiency of the EV motor will be increased, which indicates that less electrical energy is wasted as heat. Consequently, less carbon will be emitted during the process, meeting the environment protection demand.

Furthermore, liquid cooling benefits the society and brings economic development. Effective thermal management significantly extends the total lifespan of the motor and prevents a phenomenon known as "performance derating", which occurs when a vehicle's onboard computer forces the car to slow down or limit its power output in order to protect its internal hardware from damage caused by high temperature. Preventing this issue will ensure more reliable public transport networks and decrease the long term maintenance costs for individual vehicle owners.

2. Historical Context and the Evolution of Cooling Technologies

2.1. Early Developments and the Limitations of Air Cooling

In the 20th century, initial research on cooling methods for electric motors was predominantly led by major industrial entities like Hitachi, along with early electrical engineering pioneers. Their efforts initially focused on natural air cooling and passive heat dissipation methods. As motor power increased, forced air cooling utilizing external fans was developed and widely applied.

However, these traditional methods soon met limitations. Scholars like Thomas A. Lipo proposed that the thermal constraints were the problem that limited increased motor power. Without advanced cooling, commercial high- power density motors can continuously operate at only about 5kW/kg before temperatures become unmanageable and cause thermal fatigue [1].

Nowadays, electric motors have changed its focus to liquid cooling, which benefits more in various aspects compared to traditional methods.

2.2. The Transition to Liquid Cooling Architectures

Multiple studies have shown that liquid cooling significantly increases both the overall cooling efficiency compared to traditional cooling methods and the achievable power density within the motors themselves [2].

A typical liquid cooling system operates through complex heat transfer mechanisms and includes circulation pumps, intricate cooling jackets, and external radiators or heat exchangers. By circulating a liquid coolant— which has a high specific heat capacity compared to air— through engineered channels surrounding or within the motor, thermal energy can be rapidly absorbed and transported away. Furthermore, recent research strongly underscores the advantages and limitations of direct liquid cooling specifically engineered for compact machines [2].

This transition represents a superior cooling method because it allows for the maintenance of temperature stability, enabling the motor to operate continuously at its highest efficiency without triggering thermal derating protocols. Comprehensive comparisons of electro- thermal performance prove that advanced liquid cooling techniques for EV motors surpasses the traditional cooling methods [3]. Modern liquid cooling systems utilizing redesigned cooling ducts and heat exchangers can successfully push the power-to-dimension ratio of electric motors up to 25kW/kg [4].

3. Advanced Coolants: Nanofluids

3.1. The Emergence of Nanofluid Technology

While standard liquid coolants, such as water and ethylene glycol mixtures, are effective heat transfer fluids, the demand for higher power densities has pushed the development of even more capable heat transfer fluids. Current global research trends have shifted specifically toward the application and optimization of nanofluids. Nanofluids are engineered colloidal suspensions of nanometer- sized particles dispersed within a traditional base fluid.

The application of these nanoparticles alters the thermophysical properties of the fluid, which increases its thermal conductivity. For example, pioneering studies conducted by researchers such as Asim Aamir on hybrid nanofluids have shown that these advanced fluids can extract heat at exceptionally high rates [5]. This rapid heat extraction capability is important for the liquid cooling of high power density EV motors, where the peak of thermal temperature can occur in a matter of seconds during hard acceleration. Furthermore, research into the entropy optimization and heat flux analysis of Maxwell nanofluids configured by an exponentially stretching surface with velocity slip provides support for their thermodynamic performance [5]. Furthermore, the advancement of cooling fluids include not

only nanofluids, direct refrigerant cooling is also another development. Specific mixed refrigerants can maintain high heat transfer efficiency through evaporation while simultaneously reducing global warming potential and flammability risks under high temperature conditions [6].

3.2. Empirical Performance Gains with Nanofluids

The theoretical benefits of nanofluids translate into significant performance gains in real world applications. A major study led by Kumari revealed that by applying nanofluids within electric vehicle thermal management systems, the operating temperature of critical components decreases by up to 5.26% when compared to standard ethylene glycol coolants [7]. This decrease in temperature may seem modest as a percentage, but it can represent the difference between maintaining optimal efficiency and triggering thermal degradation of the motor's internal insulation.

Further studies have revealed more improvements when nanofluids are applied to specific motors. When advanced nanofluids were utilized in brushless Direct Current (DC) motors, the overall thermal management efficiency exceeded that of plain water, reaching an impressive efficiency rating of 78% [8]. Specific formulations, such as Al_2O_3 - TiO_2 /water hybrid nanofluids circulating within the liquid cooling jackets of brushless DC motors, have demonstrated potential for the synergistic control of internal flow and thermal performance[8]. These advancements indicate that the future of EV cooling depends not only on mechanical hardware, but also on advanced chemical optimization of coolants.

4. Multi- Scale Liquid Cooling Architectures and System Integration

4.1. Integration at the Micro and Component Scale

The advancement of EV thermal management is a multi-scale engineering challenge. Chinese research, has focused on how liquid cooling can be applied into different systems. At the micro- scale, research has demonstrated that incorporating liquid cooling with ultra- compact micro centrifugal pumps can effectively maintain the suitable temperature for the systems[9]. These integrated systems, which often uses printed permanent magnet synchronous motors, represent the forefront of thermal management [9].

At the component scale, researchers are also continuously finding other mechanical methods that can improve the efficiency of liquid cooling for motors. An example is the targeted alteration and optimization of the cooling pipe diameter and internal structure [10]. By designing the liquid cooling pipe structures, engineers can minimize thermal resistance and maximize the surface area available for heat transfer, significantly improving the cooling in EV drive motors [10].

4.2. System Level Synergy and Hybrid Powertrains

Moving beyond individual components, other research concentrates on the efficiency of liquid cooling within hybrid electric cooling networks. The design of innovative and integrated systems is important for hybrid electric vehicles

(HEVs), where both the internal combustion engine (or high-capacity power battery) and the electric traction motor require simultaneous thermal regulation. Direct liquid cooling is emerging as a highly competitive strategy for these complex structures because it provides minimal thermal resistance and a highly compact, low weight structure compared to indirect cooling methods [11]. These advanced designs are engineered to decrease the difference in temperature across the vehicle's powertrain and lower the operating temperature when the motor works [12].

Many thermal modeling is required to achieve this level of system synergy. Studies involving the thermal modeling of induction motors combined with liquid cooling optimization across various EV drive cycles are essential for predicting how the vehicle will behave under real-world driving conditions, ranging from stop-and-go city traffic to sustained highway speeds[13]. Furthermore, specialized applications continue to emerge; for instance, experimental studies have demonstrated the high effectiveness of liquid immersion cooling package modules specifically designed for vehicle Electric Power Steering (EPS) motors [14]. Immersion cooling, where the component is submerged directly in a dielectric coolant, increases the heat transfer rate by orders of magnitude compared to standard methods and represents a critical innovation for future Li-ion battery and motor cooling [15].

This systematic integration of multi- scale liquid cooling structures across different EV powertrain configurations is a major difference and interest in modern research. Rather than treating motor cooling and battery thermal management as separate engineering domains, current research analyzes synergistic, system level designs that improves the overall energy efficiency of the vehicle. By analyzing both international studies on direct liquid cooling in compact machines with domestic Chinese research on integrated thermal drive systems, a highly potential of cooling methods is proposed, revealing previously unexplored optimization opportunities.

5. Present Limitations and Key Issues to be Solved

5.1. System Complexity, Cost Effectiveness, and Manufacturing

Despite the many evidence that liquid cooling provides higher heat transfer efficiency than traditional methods, the technology still has its drawbacks and possesses several critical limitations. For example, the complexity of the hardware. A liquid cooling system is more complex and structurally demanding than an air cooling system due to the need for circulation pumps, extensive pipeline routing, heat exchangers, and highly robust sealing structures to prevent leaks.

This complexity directly causes an increase in manufacturing costs and vehicle weight. Therefore, a key issue that must be continuously addressed is the balance of system complexity and the expense. While liquid cooling offers better thermal performance, the application of additional components and specialized working fluids increases the difficulty of manufacturing. However, optimizing system design—such as utilizing hybrid phase change materials (PCM) with metal foam and integrating hybrid cold plates—can reduce the overall weight of the

cooling system by up to 53% and cut power consumption by 90% compared to baseline designs [16]. Future research should focus on how to balance the enhanced cooling benefits with a modest cost, long term reliability, and maintenance requirements.

5.2. Coolant Stability and Thermal Uniformity

In advanced, next generation systems, new specific challenges arise, particularly regarding the use of advanced coolants. Issues such as the long-term chemical and physical stability of nanofluids remain a question. Nanoparticles have a tendency to agglomerate or settle out of suspension over time, especially under the continuous vibration and varying temperatures experienced in EV motors. This instability can lead to clogged channels and degradation of cooling performance.

Furthermore, even with advanced fluids, maintaining a perfectly even temperature distribution across the entire stator and rotor of the motor remains incredibly difficult, and uneven temperature distribution still requires further improvement and study. This leads to the issue of thermal management efficiency under high power density conditions. As EV motors become increasingly compact and powerful, the internal heat flux density rises. This poses challenges to the cooling capacity of current liquid cooling systems.

Engineers should further address on how to optimize coolant flow distribution, alter channel geometry design, and enhance heat transfer surfaces to achieve efficient heat dissipation under strict spatial limitations. Maintaining strict temperature uniformity is essential to prevent localized thermal hotspots. If these hotspots are not managed, they will rapidly degrade the motor's internal electrical insulation, and impact both immediate performance and the lifespan of the hardware.

6. Research Methodology and Feasibility in Thermal Management Studies

6.1. Interdisciplinary Approaches to Evaluation

Evaluating liquid cooling technology requires a highly robust and multi aspect methodological approach. Because liquid cooling involves complex intersections of classical physics, mechanical engineering, advanced materials science, and broader energy technology, a interdisciplinary research method is necessary.

In modern academic reviews of this subject, the literature research method serves as the primary foundational approach. By systematically collecting, analyzing, and summarizing academic journal articles, peer- reviewed conference papers, and published industry reports related to NEV thermal management, researchers can accurately catch the current progress of the field. Furthermore, descriptive research methods are essential to clearly explain the working principles, internal structures, and complex classifications of various liquid cooling systems, resulting in a solid theoretical foundation.

To acquire meaningful conclusions, researchers should apply both qualitative and quantitative analysis. Qualitative analysis is vital for evaluating the broader advantages, potential disadvantages, and the technical challenges of a

system. On the other hand, quantitative analysis is used when comparing hard empirical data, such as specific heat transfer rates, precise temperature reduction percentages, and total efficiency improvements reported in published experimental studies. In addition, modern research relies heavily on the simulation method; by deeply examining numerical models and computational fluid dynamic (CFD) simulations, engineers can understand and predict cooling performance under a various conditions without needing to physically build every prototype. Finally, functional analysis methods are applied to examine how each specific component—whether it be the pump, the chemical makeup of the coolant, the radiator, or the microscopic channel design—contributes to the thermal performance of the vehicle.

6.2. The Novelty and Feasibility of Integrating Theory with Practice

One of the most significant novelties in modern thermal management research is the systematic integration of advanced theoretical studies (like nanofluid properties) with practical EV application constraints. While existing laboratory studies have investigated nanofluid thermal properties in controlled settings, modern reviews bridge the gap between theoretical potential and the realities of real world electric vehicle implementation challenges.

By synthesizing recent advances in specific hybrid nanofluids (such as the Al_2O_3 - TiO_2 /water systems mentioned before) with hard, practical constraints—such as the actual electrical power consumption of the circulation pump, the long term stability of the fluid under intense vibration, and the expenses required for global production—researchers provide a evaluation framework that transcends purely academic material studies. This integrative approach offers insights into how advanced coolant formulations can be applied in the next generation of EV thermal management systems.

This approach is highly feasible from both technical and academic view. Technically, liquid cooling technology has already been successfully and commercially released in numerous flagship electric vehicle models by leading global manufacturers such as Tesla, BYD, and BMW. This widespread application demonstrates its technical maturity and practical viability in real world applications. The continuous development of advanced coolants, ranging from proprietary dielectric fluids to hybrid nanofluids, alongside highly innovative channel designs and micro scale heat exchangers, indicates a technological trajectory for continuous performance improvement. This ensures that ongoing research and reviews in this domain are deeply grounded in established, reliable engineering principles.

Furthermore, from an academic perspective, the vast amount of peer reviewed data available in databases like Google Scholar, Science Direct, IEEE Xplore, and Web of Science ensures that rigorous, data driven comparisons can be drawn, establishing a solid foundation for systematic analysis.

7. Future Directions and Suggestions

7.1. Bridging the Gap Between Laboratory and Road

As the global demand for vehicle electrification increases, the research addressing these thermal management challenges possesses significant academic and practical value. The

continuous alignment of engineering research with massive international policy frameworks, for example the EU's carbon neutrality goals and China's strict industrial efficiency protocols, ensures that the findings related to liquid cooling will remain relevant and industrially impactful for decades to come.

Future research should target the identified limitations. Studies can start from purely theoretical efficiency gains to system lifecycle analyses. By identifying current hardware limitations, fluid instability issues, and future development directions, ongoing research can contribute to the automotive field. The goal is to provide highly feasible, cost effective engineering recommendations that can successfully bridge the gap between controlled laboratory research and market commercial application.

7.2. Expected Evolution of the Field

It is expected that the field will produce increasingly comprehensive systems that can connect between motor cooling, battery conditioning, and climate control. A comparison of different cooling methods will continuously prove the dominance of liquid cooling. Future EV thermal management will likely rely on smart, adjusting liquid cooling networks that applies AI- driven micropumps and stable nanofluids. Integrating Artificial Intelligence (AI) and Machine Learning (ML) into thermal management systems will enhance control by analyzing real time temperature data to optimize cooling adjustments and proactively detect early signs of thermal runaway or battery degradation [17]. By analyzing the latest research progress from both international and domestic studies, the global researchers will continue to demonstrate the efficiency advantages of liquid cooling for electric vehicles over traditional methods, paving the way for sustainable and high performance global transportation.

8. Conclusion

In conclusion, the thermal management of electric vehicle motors is a engineering domain that involves the efficiency, safety, and longevity of the modern electric powertrain. As an electric motor operates, the current flowing through its copper windings naturally generates heat. If this heat is not quickly removed, the temperature of the copper rises. This increased temperature causes copper loss which leads to greater power losses. Ultimately, this creates a negative cycle where electrical energy from the battery is wasted as heat rather than being converted into mechanical power to drive the car. The transition from traditional air cooling to complex liquid cooling structures represents a evolution to meet the increasing power density demands of modern electric motors.

The integration of advanced materials, particularly hybrid nanofluids, shows the potential to increase thermal efficiency boundaries, achieving heat extraction rates and temperature reductions that were previously thought impossible. However, as this review has highlighted, researchers should balance the complex engineering trade offs regarding system weight, manufacturing complexity, cost expenses, and the long term chemical stability of these advanced fluids. Through interdisciplinary research and multi scale system optimization, the improvement of liquid cooling technology will continue to be a central issue in the global automotive industry's successful production of next generation, high efficiency New Energy Vehicles.

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