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Thermal Management of Traction Motors in Electrified Vehicles: A Critical Review on Cooling Technologies and Future Directions

Xinyang Chen

Suzhou University of Technology
1563692596@qq.com

Abstract:

As sustainable transportation solutions, New Energy Vehicles (NEVs) have gained global prominence amidst escalating energy crises and environmental challenges. The operational stability and energy efficiency of traction motors—critical to NEV powertrain performance—are fundamentally dependent on advanced thermal management systems. This paper systematically reviews motor cooling technologies, including air cooling , liquid cooling , and evaporative cooling. Through patent analyses and case studies such as the Audi e-tron GT's dual-loop liquid cooling system, the study identifies emerging trends in hybrid cooling integration and intelligent thermal regulation. The review concludes that next-generation cooling systems must balance efficiency, reliability, and lightweight design to enhance motor longevity and reduce energy consumption while addressing evolving performance demands in NEV applications [4].

Keywords: New Energy Vehicles (NEVs); motor cooling systems; air cooling; liquid cooling; coolant flow velocity; Audi e-tron GT

1. Introduction

With the increasingly severe global climate change issues and growing concerns over energy consumption, New Energy Vehicles (NEVs) have emerged as a pivotal trend in future transportation due to their green and clean characteristics. As one of the core components of NEVs, electric motors face escalating thermal challenges as their power density and rotational speeds continue to rise. Elevated temperatures not only degrade the performance and lifespan of critical motor components such as insulation materials and bearings but also reduce overall motor efficiency. The quality of motor performance directly determines the operational effectiveness of electric vehicles [29]. Under high-power and high-speed operating conditions, motors generate substantial heat, which accelerates insulation aging and efficiency losses. Consequently, research on motor cooling systems has become vital for ensuring motor stability and reliability in NEV development. Current mainstream motor cooling technologies include natural air cooling, forced air cooling, liquid cooling, and evaporative cooling (Figure 1). Each approach possesses distinct application scenarios and advantages. This paper systematically examines the working principles, comparative strengths and limitations, application prospects, and implementation potential of these cooling technologies in NEV traction motors.

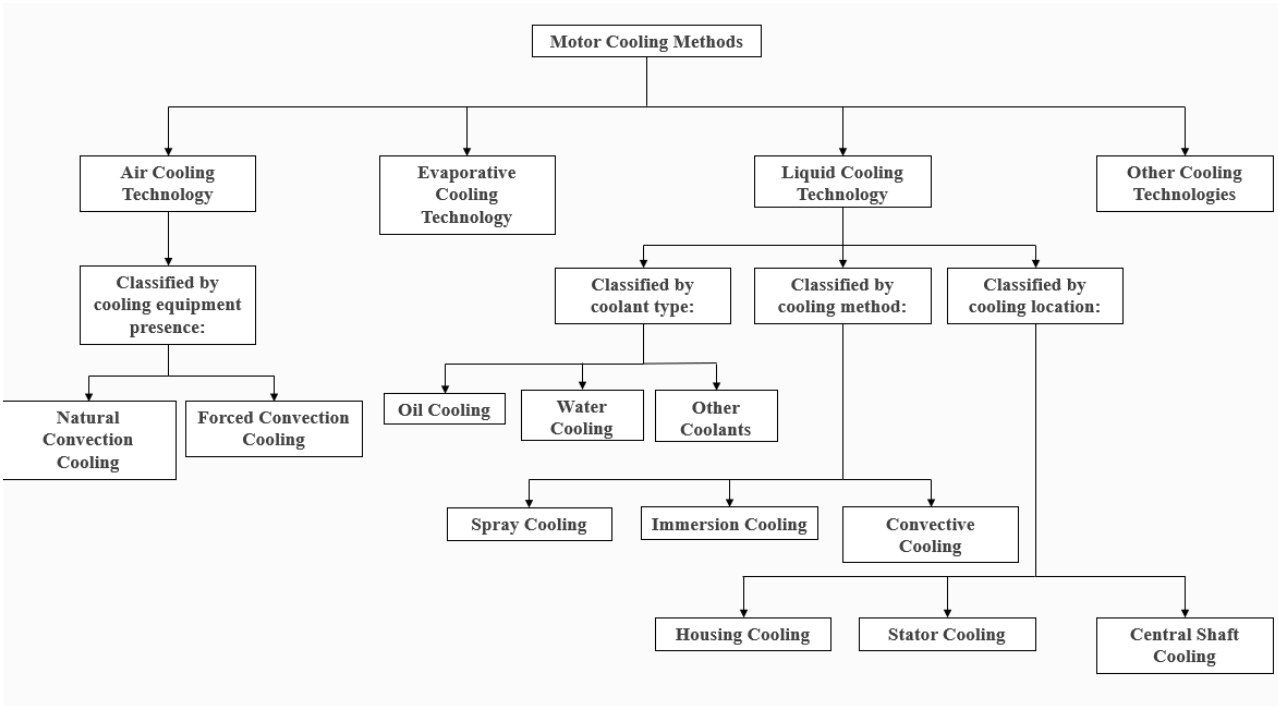

Figure 1: Current mainstream motor cooling technologies and classification

2. Basic Principles and Development of Motor Cooling Systems in New Energy Vehicles

2.1 Air Cooling Technology

Air cooling technology, an early-developed technique [31], serves as the most fundamental cooling method. Based on differences in airflow driving mechanisms, it can be categorized into natural air cooling (natural convection heat dissipation) formed by temperature gradients and forced air cooling (forced convection heat dissipation) achieved through mechanical devices generating directed airflow [16]. These two modes demonstrate complementary application scenarios in industrial practice.

2.1.1 Natural Air Cooling (Natural Convection Heat Dissipation)

The application of natural air cooling technology for motor heat dissipation primarily relies on thermal convection through gaseous media. In conventional scenarios, natural convection mechanisms utilize temperature gradients to drive airflow for heat exchange. This commonly employed in low-power motor systems. Studies indicate that optimized heat sink topology designs can significantly enhance thermal conduction efficiency in passive cooling systems [16]. However, as the power and rotational speeds of electric vehicle traction motors continue to increase, natural air cooling becomes inadequate when motor power density exceeds the critical threshold of 3.5 W/kg. Engineering practice data [18] demonstrates that natural convection cooling is only viable for open-structure motors with axial lengths exceeding 300 mm, which fundamentally conflicts with NEV lightweight design requirements.

2.1.2 Forced Air Cooling (Forced Convection Heat Dissipation)

In forced air cooling technology, engineers typically employ power-driven devices (e.g., axial fans) to establish forced convection heat dissipation structures. This design actively drives airflow, effectively enhancing heat exchange intensity between internal and external environments [27]. Compared to natural convection methods, the core advantage of forced cooling lies in its ability to significantly increase heat transfer coefficients to 20-300

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W/(m²·K), thermodynamically improving motor cooling efficiency [30]. While air cooling solutions demonstrate cost-effectiveness and structural simplicity in engineering implementation, operational challenges such as noise pollution, mechanical vibrations, and limited heat transfer efficiency restrict their application scope. Nevertheless, for space-constrained NEV traction motor layouts where liquid cooling systems face installation complexity, forced air cooling retains irreplaceable engineering value despite exhibiting 21%-27% lower heat exchange efficacy compared to liquid cooling media, when considering comprehensive manufacturing costs and technical feasibility [1].

In the field of electric motor thermal management, air cooling systems have established a comprehensive technological framework. The U.S. patent (US6011331A) demonstrates an axial-flow heat dissipation device that utilizes aerodynamic principles to construct cyclic air ducts, improving heat dissipation efficiency by 23%–28%. This innovative design optimizes blade inclination angles and airflow guide housing coordination, providing critical technical parameters for thermal balance control in NEV powertrains. Its fluid simulation model remains a benchmark framework for related research.

Emerson Electric's patented technology (US6011331A) [26] achieved breakthroughs in motor thermal management. This solution employs three coaxially arranged centrifugal fan assemblies, whose layered configuration forms dual-cycle cooling channels. A specially designed secondary airflow guidance system enables targeted cooling for power modules. Through fluid dynamics simulation optimization, thermal distribution across PCB layers is reconfigured. This composite cooling architecture reduces winding temperature rise by 23% and decreases power device junction temperature fluctuations by over 15%, significantly extending critical components' service life. The rotor assembly integrates a three-stage bladed impeller (see Figure 2), working synergistically with centrifugal fans 21 and 17. Based on the Venturi effect, this device creates negative-pressure airflow in the stator cavity, achieving efficient heat exchange through forced convection.

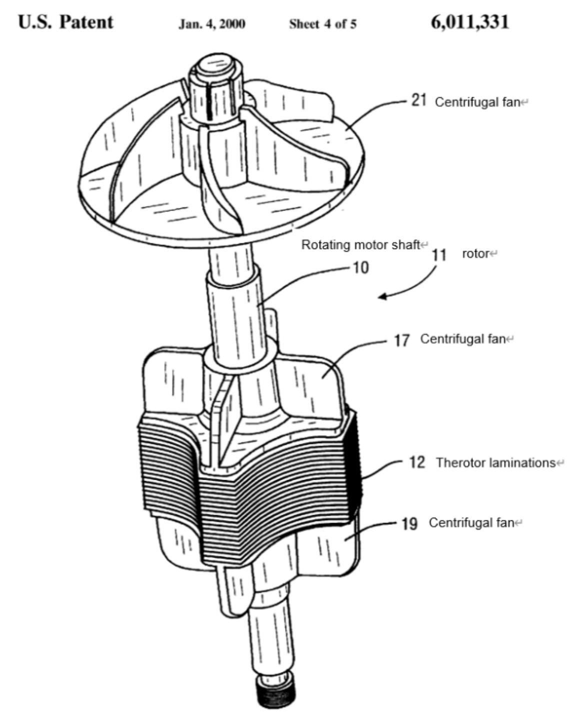


Figure 2: The structure of the rotor assembly

2.2 Liquid Cooling Technology

Liquid cooling systems employ closed-loop circulation circuits within motor housings, utilizing a multi-stage heat transfer architecture composed of water jackets, stator cooling channels, and rotating component cooling pipelines. This design enables gradient heat exchange effects between the coolant and high-temperature motor regions. Liquid cooling solutions are particularly suited for high-power motors where natural cooling proves inadequate [18]. By rationally designing cooling systems with internal or external circulation channels, heat dissipation capacity can be substantially enhanced.

Common coolants in liquid cooling systems include: Water, Water-ethylene glycol mixtures, Transformer oil.

Table 1: Physical Properties of Coolants Commonly Used in Liquid Cooling Systems at Standard Temperature and Pressure

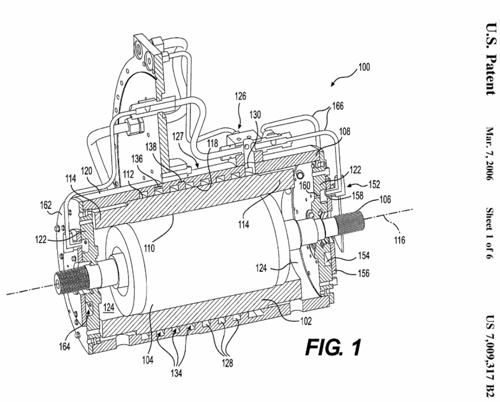
Coolant	Density / (kg/m^3)	Thermal conductivity / (W/(m·K))	Specific heat capacity / (J/(kg·°C)
Water	998.2	0.600	4183
Transformer oil	866.0	0.124	1892
Water-ethylene glycol mixtures (Volume fraction 50%)	1073.4	0.380	3281

2.2.1 Water Cooling

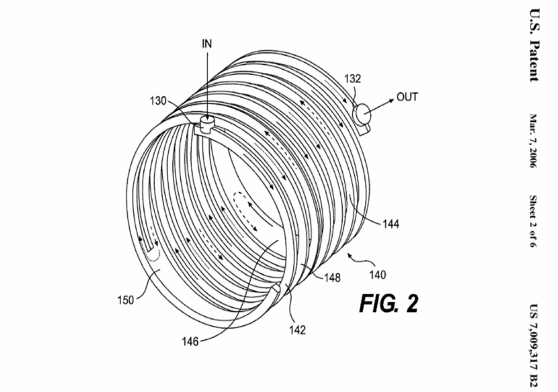
Water serves as an ideal coolant due to its high specific heat capacity and thermal conductivity, alongside advantages of non-toxicity and low cost. However, its application faces challenges including pipeline corrosion risks, complex plumbing requirements, and a high freezing point (0°C) that compromises cooling efficacy in cold climates. Incorporating ethylene glycol solutions effectively lowers the freezing point (-35°C at 50% vol.) and enhances system adaptability [21]. Mandatory additives such as anticorrosion and antifoam agents mitigate pipeline degradation.

For thermal management in medium-low power motors, external stator cooling configurations are widely adopted. These systems feature water jackets integrated into motor housings, leveraging convective heat transfer between coolant and metal components. Three primary channel geometries dominate: Annular channels maximize heat dissipation through extended contact surfaces. Helical channels minimize pressure drop (typically <15 kPa) via optimized flow trajectories. Axial channels eliminate thermal accumulation in longitudinally extended motors by maintaining axial temperature gradients below 8°C/m [25].

Water Jacket Cooling (Liquid Cooling) U.S. Patent 7,009,317 B2 proposes a representative implementation. Its schematic diagrams (Figures 3 and 4) demonstrate a sealed coolant channel formed by the mating clearance between the stator assembly and cooling jacket. Helical cooling grooves are machined on either the inner or outer surfaces of the cooling jacket, collectively forming cooling ducts with the stator or exterior sleeve. This patented innovation addresses thermal challenges in high-power-density electric motors through its helical groove design and integrated jet system, particularly suited for mobile equipment due to high efficiency, ease of maintenance, and strong adaptability.



Figures 3: the motor



Figures 4: the cooling jacket.

Water cooling systems feature complex architectures and bulky volumes, with inherent leakage risks associated with coolant circulation. These characteristics fundamentally conflict with NEV motor development requirements for compactness, operational efficiency, lightweight design, high power density, and superior reliability[28].

2.2.2 Oil Cooling

Oil cooling technology employs dielectric oil-based coolants, demonstrating superior insulation properties compared to conventional water cooling solutions. This system comprises two distinct cooling modes: indirect and direct approaches [8].

Indirect Cooling utilizes asymmetric heat transfer pathways, incorporating flow channels within motor housings and stator/rotor core components to achieve gradient heat dissipation via oil circulation.

Direct Cooling adopts immersion thermal management strategies, enabling direct coolant contact with high heat-flux regions (e.g., windings) for convective heat exchange. These architectures diverge in design principles: Enhanced dielectric parameters (>30 kV/mm) mitigate electrical breakdown risks. Optimized heat transfer efficiency (<15°C thermal differentials) improves thermal uniformity.

Direct oil cooling systems achieve direct contact between the coolant and internal heat-generating components, offering extremely high heat dissipation efficiency. This makes them an effective solution for high-power-density motors. However, additional cooling devices are required for the spent oil, which reduces motor reliability and increases costs [17].

Indirect oil cooling technology involves arranging circulating oil channels (oil jacket cooling) within the stator and rotor components inside the motor housing. Heat is dissipated through convective heat transfer with the coolant. Compared to direct oil cooling, this system avoids direct contact between the coolant and rotating parts, sig-

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nificantly reducing fluid friction losses during high-speed rotor operation.

2.3 Evaporative Cooling

Additionally, evaporative cooling technology can also be applied to motor cooling. This method utilizes phase-change cycles of low-boiling-point, high-insulation coolants to effectively dissipate heat. When the coolant contacts high-temperature motor components, it rapidly vaporizes by absorbing heat. The gaseous medium is then condensed back to liquid in a condenser, achieving continuous heat transfer through phase changes. Evaporative cooling can be categorized into three types based on different criteria::

1. By boiling point: Low-temperature evaporative cooling and room-temperature evaporative cooling.
2. By structural configuration: Tube-in cooling and immersion cooling.
3. By circulation mechanism: Natural circulation (driven by coolant density differences) and forced circulation (using pumps). This method significantly enhances cooling efficiency through phase-change processes [25].

Experimental comparisons demonstrate that evaporative cooling outperforms traditional oil cooling and external water cooling, with a quantified relationship established between liquid coolant storage volume and thermal conductivity characteristics [32].

3.Summary of Cooling Methods

Table 2: Advantages and Disadvantages of Various Cooling Methods:

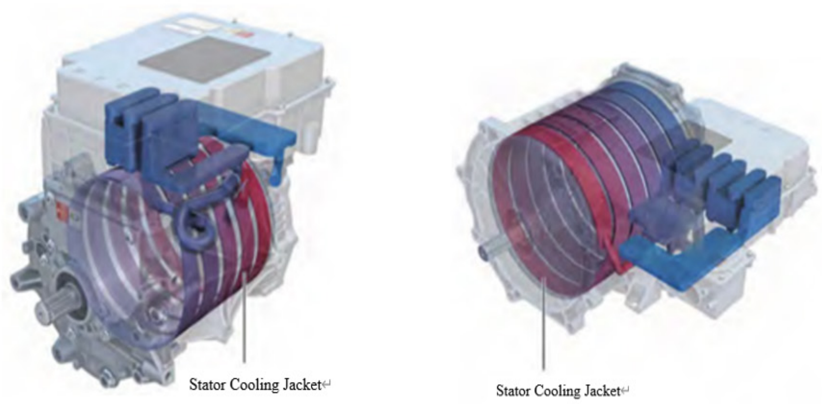
Cooling Methods	Advantages	Disadvantages
Air Cooling Technology	High cost-effectiveness;[5] Low failure rate; Low failure rates;	Limited cooling capacity; High environmental sensitivity;[24]
Liquid Cooling Technology	High heat dissipation efficiency; Low noise;	Large volume and mass; High cost; Difficult maintenance;
Evaporative Cooling	High cooling efficiency; Low energy consumption; High reliability;	Complex system architecture; Immaturity in NEV applications due to cost and safety constraints;

4. Application of Cooling Systems in Practice

Table 3: the traction motor cooling systems currently implemented in New Energy Vehicles (NEVs) available on the market:

Motor Model (or Corresponding Vehicle)	Cooling Solution	Technical Details
Tesla Model 3	Liquid cooling (water jacket cooling) [6]	Motor stator housing integrated with water jacket, coolant circulation for heat removal [10].
BYD Dolphin/Han EV Motor	Liquid cooling (water jacket cooling)	Water jacket enveloping stator, intelligent thermal control system integrated with battery cooling.
BMW iX3/i4 Motor	Liquid cooling (water jacket cooling)	Water jacket integrated into motor housing, coolant flowing through stator exterior.
Porsche Taycan Rear Axle Motor	Oil cooling (oil jacket cooling)	Rotor shaft oil channels + stator spray cooling, direct-contact heat dissipation.
Zeekr 001 Dual-Motor Version Motor	Oil cooling (oil jacket cooling)	Internal oil circulation channels, direct oil cooling for rotor and stator[20].
Wuling Hongguang MINI EV (Early Motors)	Air cooling (natural convection)	No active cooling devices, relying on airflow during vehicle motion[23].

With the advancement of New Energy Vehicles (NEVs), numerous automakers are developing high-performance electric sports cars. Compared to traditional internal combustion engine sports cars, NEV motors can deliver peak torque almost instantaneously. A representative example is Audi's e-tron GT, a pure electric sports car achieving 0-100 km/h acceleration in 4.2 seconds (quattro version) and 3.4 seconds (RS variant) [22]. As an electric performance vehicle, it demands exceptional cooling efficiency. Both front and rear axles employ Permanent Magnet Synchronous Motors (PMSMs), with their drive motor configurations and cooling architectures detailed in Figures 5. To ensure optimal thermal performance, the cooling system utilizes G12 evo coolant (ethylene glycol-based antifreeze) [9] through liquid cooling technology.



Figures 5: Front/Rear Electric Drive Cooling

5. Impact of Coolant Flow Velocity in Liquid Cooling Systems

Liquid cooling dominates NEV motor thermal management, with coolant flow velocity critically influencing cooling performance through:

5.1 Flow Regime Effects

The coolant's flow regime (laminar vs. turbulent) directly governs heat transfer efficiency [19]. Under low flow velocities, laminar flow dominates with orderly fluid layers exhibiting minimal mixing, resulting in inferior heat exchange. Conversely, elevated velocities induce turbulent flow characterized by chaotic fluid motion and intensive mixing, which enhances heat transfer coefficients by 2-3× compared to laminar conditions [3]. Specifically:

· Laminar flow: Heat transfer coefficients typically range 50-200 W/(m^2·K)

· Turbulent flow: Coefficients escalate to 300-1000 W/(m^2·K), significantly improving cooling capacity

5.2 Variations in Heat Transfer Efficiency

Increasing flow velocity enhances the convective heat transfer coefficient, thereby improving the motor's internal heat dissipation capacity [12]. For instance, in water cooling systems, elevated flow velocities significantly reduce internal motor temperatures. However, excessive velocities may induce thermal saturation [7], where further velocity increases yield diminishing cooling returns while escalating energy consumption.

5.3 Pressure Drop Effects

Higher flow velocities amplify pressure losses (ΔP) within cooling channels [2]. Extreme velocities not only increase pumping power demands but also compromise system reliability. Thus, practical designs require balanced optimization between heat transfer efficiency and pressure drop to identify an optimal velocity range.

5.4 Coolant Property Impacts

Different coolants (water, ethylene glycol solutions, oil) exhibit distinct heat transfer efficiencies due to their physical properties[15]:

· Water: Superior thermal conductivity (0.6 W/m·K) and specific heat capacity (4.18 kJ/kg·K) enable effective cooling even at low velocities (0.1–0.3 m/s) [14].

· Ethylene glycol solutions: Slightly reduced cooling efficiency vs. water, with adjustable freezing points via concentration modulation (optimal velocity: 0.15–0.25 m/s) [11].

· Oil: Lowest thermal conductivity (0.1–0.15 W/m·K) necessitates higher velocities for comparable cooling, yet excessive speeds induce severe pressure drops due to high viscosity (kinematic viscosity >20 cSt).

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Conclusion

Coolant flow velocity profoundly impacts motor cooling performance. Design optimization requires holistic evaluation of flow regimes, heat transfer efficiency, pressure losses, and coolant properties to identify energy-efficient velocity ranges that balance thermal management and operational sustainability.

6. Future Research Directions

New energy vehicle motor cooling systems will evolve towards high efficiency, intelligence, integration, and lightweight design to meet escalating power demands. Key trends include:

1. Hybrid cooling technology integration: Combining liquid, air, and oil cooling methods to enhance efficiency and system stability.
2. Novel coolant development: Discovering materials with superior thermal conductivity and lower costs to replace conventional liquid coolants.
3. Advancements in oil cooling: Compact, high-efficiency oil cooling systems will dominate for high-power motors, though breakthroughs remain needed in oil circuit design and component compatibility.
4. Reliability and maintainability: Durable, service-friendly designs to reduce lifecycle costs and extend operational longevity.

As the NEV market continues to expand [13], motor cooling systems must advance synergistically with performance requirements. Future developments will prioritize energy-efficient, smart, and sustainable solutions, leveraging multi-technology integration to address high-power traction demands while elevating system robustness and reliability.

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