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Exploring Optimization Strategies for Thermal Management Systems of New Energy Vehicles

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***Abstract*—*With the advancement of industrialization, new energy vehicles (NEVs) have become crucial for mitigating air pollution and global warming, and the thermal management system (TMS) has emerged as a key component affecting vehicle safety, performance, and comfort. For battery electric vehicles (BEVs), the TMS has evolved from a set of decentralized auxiliary circuits into a vehicle-level energy dispatch hub. This paper examines the heat generation mechanisms, key components, and refrigerant/coolant paths of the battery, motor/drive, and cabin air conditioning subsystems, and compares the integrated architectures of Tesla, Xiaomi, and BYD. The analysis shows that integration, intelligent control, and working fluid substitution are the main optimization directions. Integration strategies include centralized octovalve, discrete multi-valve, and direct-cooling/direct-heating schemes. Intelligent control is moving from PID to model predictive control and reinforcement learning, while the natural refrigerants R290 and R744 offer advantages in wide-temperature adaptability and low-temperature performance, respectively. In addition, immersion cooling, composite phase-change materials, digital twins, and predictive thermal management are extending optimization from hardware and algorithms to materials, cloud, and life-cycle management. Ultimately, the future competitiveness of TMS will rely on unifying structural integration, intelligent control, and refrigerant switching into a coherent engineering system under the constraints of wide-temperature-range adaptation, high-performance chip cooling, and environmental regulations.*

***Keywords*—control strategy optimization, integrated thermal management, new energy vehicles, refrigerant substitution, thermal management system**

I. INTRODUCTION

1.1 Research Background and Significance

It is an indisputable fact that the driving range of pure electric vehicles is constrained by temperature. In winter low-temperature environments, the driving range can decay by over 40%, with air conditioning heating accounting for more than 60% of auxiliary energy consumption[1][2]; in summer high-temperature environments, the battery cooling load exerts dual pressure on both driving range and charging power. The task of the thermal management system is to maintain the temperatures of the battery, motor and electronic control, and passenger cabin within efficient and safe windows across the full climate range. The optimal operating range of lithium-ion batteries is concentrated between 20°C and 40°C; beyond this range, internal resistance surges, capacity degradation accelerates, and in severe cases, thermal runaway chain reactions may be triggered[3][4]. Thermal management is therefore not merely an energy efficiency issue, but is directly linked to overall vehicle safety and power battery lifespan.

Early electric vehicles adopted a distributed thermal management architecture, in which battery cooling, motor heat dissipation, and air conditioning circuits operated independently and could not share energy. The defects of this approach are particularly acute in winter: the waste heat generated by the drive motor is dissipated in vain, while the passenger cabin has no choice but to rely on high-power PTC electric heating to maintain comfort[2]. The introduction of heat pump systems partially alleviated this contradiction; heat pumps using R134a or R744 as working fluids can raise the heating coefficient in low-temperature environments to above 2.0, offering a clear energy-saving advantage over PTC[5]. However, a single air-source heat pump is prone to sharp declines in heating capacity and frosting problems below -10°C, requiring vapor injection or coupling with motor waste heat to meet heating demands[5][6]. This means that the thermal management system must move toward integration, fusing the multiple refrigerant and coolant circuits of the battery, electric drive, and air conditioning into a single controllable whole[7][8].

Currently, integrated thermal management has become the mainstream technical direction for pure electric vehicle models. Tesla, on the Model Y, concentrates almost all mode switching on the coolant side into a single actuator through the Octovalve eight-way valve, simplifying the refrigerant piping and trading high integration for low cost and light weight. The Xiaomi SU7 adopts a multi-valve distributed architecture, networking four-way valves and plate heat exchangers, demonstrating an alternative approach in terms of waste heat cascade utilization and platform scalability. The BYD Dolphin employs a direct cooling and direct heating scheme that introduces refrigerant directly into the battery pack, eliminating intermediate heat exchange links, and combined with pulse self-heating technology, it improves low-temperature heating rates and system efficiency[9]. These differentiated routes illustrate that, even under the same physical principles, the design choices of component topology, working fluid flow direction, and control logic can profoundly influence overall vehicle energy efficiency and all-scenario adaptability; the thermal management system has thus evolved from an auxiliary temperature control device into the energy dispatch center of the entire vehicle[8][10].

Against the above background, this paper conducts a review centered on the thermal management system of pure electric vehicles, focusing on dissecting the heat generation mechanisms, key components, and refrigerant/coolant working pathways of the three major subsystems: the battery, the motor and electronic control, and the passenger cabin. Typical vehicle models such as Tesla, Xiaomi, and BYD are selected for horizontal comparison, revealing the similarities and differences of working fluid flow directions and performance trade-offs under different integrated topologies. On this basis, optimization strategies are sorted out from four dimensions: high-efficiency heat pump cycles, intelligent control, structural integration, and advanced cooling; technical challenges such as wide temperature range adaptation, new working fluid switching, and digital twins are also discussed, with a view to providing references for subsequent thermal management system design and selection.

II. OVERVIEW OF NEW ENERGY VEHICLE THERMAL MANAGEMENT SYSTEM ARCHITECTURE

2.1 Energy Flow and Basic Tasks of Vehicle-Level Thermal Management

What the thermal management system faces is not the temperature problem of a single component, but the continuously fluctuating energy difference between multiple heat sources and heat sinks across the entire vehicle. The battery generates heat sharply during high-rate charging and discharging; the drive motor temperature rises rapidly under high load; the junction temperature of power electronic devices needs to be suppressed in a very short time; and the cooling and heating demands of the passenger cabin constantly change with seasons, sunlight, and the number of occupants[11]. The generation and dissipation of this heat are not synchronized in time, and although spatially separated, they are adjacent to each other. The fundamental task of the thermal management system is to establish a controllable energy distribution channel between these fluctuating thermal loads, so that the temperature of each critical component always falls within a relatively narrow high-efficiency window.

2.2 Dynamic Balance between the Heat Generation Side and the Heat Dissipation/Absorption Side

From the perspective of energy flow, vehicle-level thermal management can be abstracted as a dynamic balance between the heat generation side and the heat dissipation/absorption side. The heat generation side covers the Joule heat and polarization heat of battery internal resistance, the copper loss and iron loss of motor windings, the switching and conduction losses of inverter power modules, as well as the power losses of the on-board charger and DC/DC converter[12]. The heat dissipation/absorption side includes the forced convection heat transfer from the front-end radiator to the environment, the heat absorption of the air conditioning refrigeration cycle in the evaporator and Chiller, and the low-grade thermal energy extracted by the heat pump cycle from the outdoor low-temperature air[13]. The energy flow between the two sides is not unidirectional: in winter, the waste heat generated by the motor and power electronics can be captured and transferred to the passenger cabin or battery pack; in summer, the same system needs to expel battery heat and cabin thermal load to the outside of the vehicle simultaneously[14]. The distribution of this cooling and heating capacity among multiple circuits depends not only on the physical connection of heat exchangers but, more critically, on the real-time switching of coolant and refrigerant flow directions by multi-way valve assemblies.

2.3 Essential Differences between Pure Electric Vehicle and Traditional Fuel Vehicle Thermal Management

Here arises a fundamental issue: the thermal management of pure electric vehicles differs essentially from that of traditional fuel vehicles. A fuel vehicle possesses an internal combustion engine that operates continuously and generates considerable heat, with coolant temperature typically stabilized above 90°C; in winter, heating can be achieved simply by introducing a small portion of engine waste heat into the heater core, consuming almost no additional fuel[15]. A pure electric vehicle has no such free heat source at all. The heat generation power of the drive motor is far lower than that of an internal combustion engine, and the temperature rise is slow; at low-temperature cold start, there is almost no surplus heat available. Therefore, winter heating must rely on high-voltage battery output, and the energy consumption of the air conditioning system directly translates into driving range loss[16]. On the other hand, the battery has much stricter temperature requirements than an engine: it can neither overheat nor overcool, and the temperature difference between cells must be controlled within 5°C; otherwise, capacity degradation accelerates and may even induce thermal runaway[17]. This means that the thermal management system must simultaneously address multiple temperature targets: the passenger cabin pursues human thermal comfort, the battery requires precise constant temperature, and the motor and electronic control focus on preventing over-temperature failure. The temperature control accuracy, response speed, and safety level of these three differ, yet they share the same set of coolant and refrigerant circuits, which inevitably leads the system architecture toward deep coupling[18].

2.4 Architectural Evolution from Distributed to Integrated

The early approach was to divide battery thermal management, motor and electronic control thermal management, and passenger cabin air conditioning into three relatively independent subsystems. The battery side relied on cold plates and Chillers for cooling or PTC for active heating; the motor side constituted a heat dissipation circuit composed of a low-temperature radiator and water pump; and the passenger cabin formed a vapor compression cycle with the electric compressor as the core[14]. The three subsystems initially exchanged cooling capacity only through the Chiller. However, with increasing integration, the introduction of four-way valves, eight-way valves, and multi-valve combinations allowed coolant to flow on demand between circuits, enabling motor waste heat to be directly used for heating the battery or passenger cabin, and allowing the heat pump refrigerant to simultaneously provide cooling capacity to both the passenger cabin and the battery[19]. This deep coupling not only reduces heat waste but also unifies previously dispersed control objectives into the global framework of vehicle energy management.

2.5 Three Typical Modes of Integrated Thermal Management

From the perspective of architectural evolution, integrated thermal management has formed three typical modes. The first takes coolant-side integration as the main line, using a highly centralized multi-way valve assembly to govern the mode switching of all coolant circuits, while the refrigerant circuit remains relatively simple; Tesla's Octovalve is the ultimate representative of this approach[20]. The second is characterized by refrigerant-side integration, introducing refrigerant directly into the battery pack to complete evaporative cooling or condensing heating, eliminating intermediate heat exchange links and the pump power consumption of secondary circuits; BYD's direct cooling and direct heating scheme falls into this category[14]. The third adopts a discrete multi-valve hybrid integrated architecture, retaining flexibility on both the coolant and refrigerant sides, networking multiple three-way valves, four-way valves, and plate heat exchangers to strike a balance between waste heat cascade utilization and platform scalability; the design of the Xiaomi SU7 roughly embodies this direction[19]. The three modes each have their trade-offs, but they all point toward a common trend: the thermal management system is evolving from an auxiliary subsystem into the energy dispatch center of the entire vehicle.

III. PRINCIPLES OF THERMAL MANAGEMENT SYSTEMS

3.1 Battery Thermal Management System

3.1.1 Temperature Control Targets and Heat Generation Characteristics

Lithium-ion batteries are somewhat excessively sensitive to temperature; their comfort zone is confined between 20°C and 40°C. If the temperature difference between cells exceeds 5°C, localized aging accelerates, and the capacity degradation of the entire pack becomes desynchronized[21]. This stringent requirement originates from the internal electrochemical processes of the battery. During charging and discharging, lithium ions shuttle back and forth between the positive and negative electrodes, while electrons perform work through the external circuit. However, this process is not completely reversible; factors such as ohmic internal resistance and polarization internal resistance convert a portion of electrical energy into Joule heat, which constitutes the main source of battery heat generation.

The Bernardi heat generation rate model divides battery heat generation into two parts: irreversible heat directly linked to current, and reversible heat caused by entropy change. At low discharge rates, reversible heat is quite noticeable, but once entering high-rate charging and discharging, irreversible heat dominates, and the temperature rise is no longer linear. What is more troublesome is internal resistance, which itself is a function of temperature and SOC. In cold weather, the electrolyte thickens, the resistance to lithium-ion movement increases, and the internal resistance can expand several times compared to room temperature, causing the heat generation to surge under the same current[22]. Therefore, at low temperatures, the battery not only needs to be heated to recover usable capacity, but its own heat generation during the heating process is also very uneven; the timing of thermal management intervention must simultaneously account for both external heating and internal heat generation.

3.1.2 Packaging Forms and Heat Transfer Paths

When heat is transferred from inside the cell to the outside, the three packaging forms—prismatic, cylindrical, and pouch—follow different paths. The thermal conductivity in the thickness direction of prismatic cells is much lower than in the length and width directions, so heat tends to accumulate right in the middle of the electrode stack[22]. For cylindrical cells, the axial and radial thermal resistances are also unbalanced, and the area between the end face of the winding core and the bottom of the casing is often a dead zone for heat dissipation. Although the thermal resistance of pouch cells in the thickness direction is small, the casing is soft and highly sensitive to clamping force and interface contact conditions. Regardless of the packaging form, for heat to travel from the innermost part of the cell to the cooling medium, it must pass through a long series of thermal resistances including positive and negative electrode materials, separator, current collectors, cell casing, thermal interface materials, and the cold plate wall. If any interface is not properly attached, the entire heat dissipation chain gets stuck there.

3.1.3 Cooling Methods

There are only a few mainstream methods for battery thermal management: air cooling, liquid cooling, direct cooling, and phase change material cooling. Air cooling was the earliest used; it blows air over the surface of the battery module to carry away heat. The advantage is simple structure and no leakage concerns, but the specific heat capacity and thermal conductivity of air are too low. Once the battery heat generation power rises, the required air volume increases sharply, the fan becomes noisy and power-consuming, and it is difficult to smooth out the temperature difference along the wind direction[23]. Liquid cooling uses an aqueous ethylene glycol solution as the coolant, driven by a water pump to flow through a cold plate attached to the bottom of the battery, carrying heat to the Chiller or radiator for discharge. The high specific heat capacity of the liquid means that a small flow rate can move a considerable amount of heat, but it adds an entire fluid circuit including water pump, expansion tank, piping, and valves, bringing additional energy consumption and weight. How the flow channels of the cold plate are arranged also directly determines the heat transfer performance and the magnitude of the temperature difference. Straight channels are easy to manufacture but have small heat transfer area; serpentine channels provide more heat exchange but with high pressure drop. Now there are also leaf-vein-mimicking channels and topology-optimized channels that strike a balance between pressure drop and temperature uniformity[24]. A study comparing four cold plate structures—leaf-vein, serpentine, straight, and honeycomb—found that the leaf-vein bionic structure had significantly lower maximum temperatures than the other three at different discharge rates, with the best overall heat dissipation performance[25]. There are also designs applying Tesla valve structures to cold plates, using the impact and vortex generated by reverse fluid flow to enhance heat transfer; the internally improved Tesla valve maintains heat dissipation capacity while having lower pressure drop, with overall performance improved by 79% compared to the traditional Tesla valve[26]. Direct cooling is more straightforward: the air conditioning refrigerant is directly introduced into the evaporator plate inside the battery pack, relying on refrigerant boiling to absorb heat, eliminating the intermediate coolant layer and resulting in a smaller heat transfer temperature difference[27]; the BYD Dolphin uses this scheme[9]. However, temperature uniformity is harder to control; uneven distribution of refrigerant in the evaporator plate, with some areas drying out and others accumulating liquid, leads to large temperature differences. One study proposed a method using coordinated control of an electronic expansion valve and an electric backpressure valve to stabilize superheat, reducing superheat overshoot by approximately 53% and recovery time by 54%[28]. Phase change material cooling is passive; materials such as paraffin wax are filled in the gaps between cells. When the temperature exceeds the phase change point, the material melts and absorbs heat, with the temperature remaining almost constant. It consumes no electricity and responds quickly. However, once the latent heat is exhausted, the cooling capacity drops off a cliff. Therefore, many studies are now working on composite schemes of phase change materials and liquid cooling, where the liquid cooling circuit continuously extracts heat from the phase change material to help it recover latent heat[29]. One study combining phase change material and liquid cooling reduced the maximum battery temperature difference by 15.87% and system pressure drop by 90.07%[30]; another using a topology-optimized cold plate with phase change material kept the maximum battery pack temperature around 41°C under 5C discharge and 2C charge cycles, with a maximum temperature difference of less than 3°C[31]. Numerical research by Khan et al. shows that an optimized cold plate using R134a refrigerant can control the maximum battery temperature at 38.1°C under 4C discharge[32].

3.1.4 Heating Methods

On the heating side, in winter the battery may freeze to minus twenty degrees Celsius; direct charging would cause lithium plating, and dendrites piercing the separator would lead to serious problems. Therefore, the first priority is to quickly warm the battery pack to a safe temperature. The PTC electric heater is the most direct method; it heats up when powered, but its coefficient of performance is always less than 1, consuming considerable electricity. A study comparing the effects of PTC and heat pump heating methods on battery aging found that the optimized thermal management strategy can simultaneously reduce energy consumption and aging rate[33]. Motor waste heat recovery can save a lot of energy; the motor is run in a low-efficiency zone to generate waste heat, which is then transferred to the battery through a heat exchanger—both Tesla and Xiaomi have adopted this approach[34]. An even more aggressive method is pulse self-heating, which causes the battery to undergo short-duration high-frequency charging and discharging internally, generating heat through its own internal resistance. The heat travels from the inside out, providing good temperature uniformity and fast heating rates; BYD has already mass-produced this technology on its blade batteries.

3.1.5 Key Components

Among the core hardware in the battery thermal management circuit, the Chiller is one. It is connected to the air conditioning refrigerant on one side and the battery coolant on the other; the refrigerant evaporates and absorbs heat inside, and the coolant is cooled and then flows back to the battery pack. One study developed an integrated dual-effect Chiller that reduces pressure drop by 35% to 62% compared to traditional designs, and reduces water pump power consumption by approximately 55% at a flow rate of 16 L/min[35]. The water pump needs a wide speed regulation range, turning slower at low loads to save electricity and running at full speed at high loads to suppress temperature rise. The expansion tank provides compensation space for the thermal expansion and contraction of the coolant while also venting air at the system high point. The density and accuracy of temperature sensor placement determine how accurate the information obtained by the BMS is; cell-level temperature acquisition has now become mainstream.

Different automakers take very different approaches to battery thermal management; the logic of liquid cooling, direct cooling, and composite schemes, as well as how the working fluid flows and how heat moves, is completely different. Tesla uses the Octovalve eight-way valve on the Model Y, which consolidates the coolant sides of the battery circuit, motor circuit, and air conditioning circuit into a single valve; rotating the valve core completes the mode switch. When the battery needs heating, the Octovalve directly connects the motor circuit and battery circuit in series, allowing the heat generated by active motor heating to be pumped into the battery pack through the coolant, eliminating the need for PTC altogether[34]. The Xiaomi SU7 takes a different path; its cold plate is attached to both sides of the cell, providing a large heat exchange area that is sufficient even at low flow rates. In terms of circuit topology, instead of a single centralized large valve, it uses multiple independent valves to form a network. When heating the battery, it can simultaneously use both the heat pump and motor waste heat as heat sources, providing high redundancy so that the failure of one valve does not cause a complete system shutdown. The BYD Dolphin's direct cooling and direct heating scheme directly extends the refrigerant piping into the battery pack. During cooling, part of the refrigerant goes to the passenger cabin evaporator and another part to the evaporator plate in the battery pack; during heating, it relies on a four-way valve to switch to heat pump mode, with the compressor discharge entering the condenser plate inside the battery pack to release heat to the battery. This eliminates the Chiller and coolant circuit, saving one level of heat exchange loss[9]. None of the three approaches is absolutely superior. Tesla pursues ultimate physical simplicity, trading valve complexity for piping simplicity; Xiaomi pursues platform flexibility and control redundancy; BYD starts from reducing heat exchange layers, using integration to raise the energy efficiency ceiling while bearing the engineering challenges of temperature uniformity control.

3.2 Motor and Electronic Control Thermal Management System

3.2.1 Heat Generation Characteristics and Temperature Control Requirements

The losses generated by the drive motor during energy conversion are released in the form of heat. The sources mainly consist of three parts: the copper loss of the stator windings is proportional to the square of the current, dominating heat generation under high-torque low-speed conditions; the iron loss of the stator core originates from hysteresis and eddy current effects in the alternating magnetic field, intensifying as the speed increases; although the eddy current loss of the rotor permanent magnets is relatively small in magnitude, it easily forms localized hot spots due to the limited heat dissipation path. Once the permanent magnet temperature exceeds the allowable upper limit of its grade, the coercivity will undergo irreversible degradation[36]. The IGBT or SiC modules in the motor controller generate switching losses and conduction losses during high-frequency switching; when the junction temperature exceeds the rated upper limit of 150°C to 175°C, the current-carrying capacity of the device drops sharply, and in severe cases, over-temperature protection is triggered, directly cutting off power output[37]. Unlike batteries, the allowable temperature window of the motor system is relatively wide; winding insulation typically withstands temperatures above 180°C, and the coolant outlet temperature is allowed to reach 65°C to 75°C. This characteristic gives the motor circuit a dual identity in vehicle-level thermal management: it is both a heat source that needs cooling and a source of low-grade waste heat that can be extracted in winter.

3.2.2 Water Cooling and Oil Cooling Technologies

As the most widely used motor cooling method at present, water cooling relies on coolant flowing through the internal water jacket of the stator housing to remove heat through convective heat transfer. Its fundamental limitation is that there are at least two layers of solid wall between the coolant and the heat source; the heat inside the winding ends and rotor must be conducted axially or radially to the stator core and then cross the housing before it can be carried away, resulting in a long heat transfer path and high thermal resistance[36]. Oil cooling technology significantly shortens the heat transfer path by directly spraying cooling oil onto the heat source surface. The oil is pressurized by an oil pump and directed through nozzles to spray onto the stator winding ends and rotor end faces; some designs also introduce cooling oil into the interior of the rotating shaft, using centrifugal force to fling it out from the gaps in the rotor laminations to directly cool the permanent magnets[38]. Oil cooling simulation studies for hairpin winding motors show that an axial configuration combined with a 2 mm nozzle diameter can achieve higher heat transfer coefficients[39]. Oil cooling and water cooling are showing a trend of combined application; the stator housing retains the water jacket as the basic heat dissipation layer, while oil cooling provides targeted cooling for the winding ends and rotor. The composite dual water circuit plus oil cooling scheme can reduce the winding temperature rise by approximately 7.2°C compared to the pure water cooling scheme[40]. In addition, a spray-heat pipe composite cooling structure proposed for YASA axial flux motors achieves rapid extraction of heat from the winding ends by simultaneously employing spray impingement and heat pipe conduction within the stator assembly[41].

3.2.3 Circuit Hardware Composition

In the hardware composition of the motor and electronic control thermal management circuit, the low-temperature radiator is arranged at the front of the vehicle, relying on oncoming airflow and the forced convection of an electronic fan to dissipate coolant heat into the atmosphere. The electronic water pump, serving as the circulation power source, is mostly a centrifugal pump driven by a brushless DC motor, with linearly adjustable speed to meet changing heat dissipation demands. The oil cooling system is additionally equipped with an oil pump, an oil cooler, and a filter; the oil cooler transfers the heat carried by the oil to the water cooling circuit or refrigerant, and the filter is used to intercept metal wear debris to prevent nozzle blockage[38]. The selection of heat dissipation base plates and thermal interface materials for power electronic devices directly affects the junction temperature performance; one study combined the cooling water from the vehicle radiator with the air conditioning outlet air for a hybrid heat sink to manage the thermal load of the IGBT module[37].

3.2.4 Waste Heat Recovery and Stalling Heating

Under normal cooling mode, driven by the water pump, the coolant sequentially flows through the motor controller heat dissipation base plate, the drive motor water jacket or oil cooler, absorbs heat and rises in temperature, then passes through the thermostat to the low-temperature radiator to discharge heat to the environment. In the low-temperature environment of winter, motor heat generation transforms from a burden into an asset. The core idea of waste heat recovery is to add a branch path in the coolant circuit leading to the heat pump evaporator side or battery heating side. Before entering the radiator, the high-temperature coolant from the motor outlet first passes through a plate heat exchanger to transfer heat to the heat pump refrigerant or battery coolant circuit[42]. Research by Tang Liang et al. calibrated the optimal opening temperature for waste heat recovery at 35°C; below this temperature, the motor's own temperature rise has not yet reached the required level, and the recovery efficiency is too low[43]. Actual vehicle test data from Wang Tianying et al. show that at an ambient temperature of -18°C, vehicles equipped with a waste heat recovery system reduced energy consumption by 35% in the first hour, and the driving range under urban conditions increased by approximately 23%[44]. When there is no waste heat available from the motor in extreme cold stationary conditions, the control algorithm can put the motor into stalling operation mode; the stator windings are fed a specific current to generate copper loss and iron loss without outputting effective torque, and all electrical energy is converted into heat, which is transported to the battery pack via the coolant[45].

3.2.5 Comparison of Motor Thermal Management Schemes of Different Vehicle Models

Different automakers have different emphases in their motor thermal management paths. Tesla Model Y connects the motor circuit and battery circuit in series through the Octovalve; when the battery needs heating, the high-temperature coolant from the motor outlet bypasses the radiator and directly enters the battery cold plate[34]. The Xiaomi SU7 adopts a directed oil cooling scheme and achieves isolated coupling between the motor side and battery side through a plate heat exchanger, with the working fluids not mixing to enhance the functional safety level, at the cost of an additional layer of heat transfer temperature difference. In some models, BYD absorbs motor coolant heat on the heat pump evaporator side, raises the temperature through the compressor, and then releases it through condensation on the battery side, using the motor waste heat as a low-temperature heat source for the heat pump[42]. Each of the three paths has its trade-offs, jointly confirming that motor thermal management solutions must be globally weighed at the vehicle level.

3.3 Passenger Cabin Air Conditioning System

3.3.1 Refrigeration and Heat Pump Heating Principles

The energy consumption pressure of the passenger cabin air conditioning in pure electric vehicles is completely different from that of fuel vehicles. After the engine is gone, winter heating relies entirely on high-voltage battery output, and in cooling mode, the compressor power consumption similarly directly reduces the driving range. The system must complete heat transfer with the highest possible efficiency, and its core architecture is based on two basic modes: the vapor compression cycle and the heat pump cycle.In cooling mode, the electric compressor compresses low-temperature low-pressure gaseous refrigerant into high-temperature high-pressure superheated vapor, which is discharged into the outdoor heat exchanger to release heat to the environment and condense into subcooled liquid. After being throttled and depressurized by the electronic expansion valve, it enters the indoor evaporator, absorbs the heat of the cabin air, boils and evaporates, and simultaneously completes dehumidification[46]. In heat pump heating mode, the flow direction is reversed through a four-way valve; the compressor discharge is directed into the indoor condenser to release heat to the passenger cabin, and the condensate, after throttling, absorbs heat from the low-temperature environment in the outdoor heat exchanger[46]. Bench tests by Liu Mingkang et al. provide quantitative results for vapor injection: under conditions of -20°C and 4000 r/min, the traditional heat pump heating capacity was only 1.93 kW, COP approximately 1.5, and exhaust temperature 104.2°C; after activating vapor injection with a relative injection volume of 22%, the heating capacity rose to 2.56 kW, COP rose to 1.88, and the exhaust temperature dropped to 72.6°C[47]. The economizer evaporates part of the liquid refrigerant and injects it into the compressor injection port, equivalent to intermediate cooling, effectively alleviating the low-temperature heating attenuation.

3.3.2 Regulation Characteristics of the Electronic Expansion Valve

The electronic expansion valve is the core actuator for regulating refrigerant flow and superheat. Liu Denghui et al. found through comparison that the electronic expansion valve is superior to the H-type thermostatic expansion valve in both superheat stability speed and fluctuation range, with the advantage being more significant at low speeds[48]. Gu Xiaoyang et al. further revealed that the refrigerant circulation flow rate has a linear relationship with the valve opening; for every 10% decrease in opening, the flow rate drops by 6% to 9%. Moreover, when the subcooling before the valve is too large, closing the valve may cause brief over-throttling and pressure fluctuations[49]. For high-temperature working conditions, Haijun Li et al., using R1234yf refrigerant for testing, found that setting the main valve superheat at 5°C achieved a maximum cooling capacity of 3.201 kW and a COP value of 1.769, representing increases of 13.9% compared to the 3°C superheat condition[[50].

3.3.3 Dehumidification Mode

The dehumidification mode must balance moisture removal and outlet air temperature. The dual-evaporator heat pump study by Tan Mingfei et al. showed that the dehumidification rate of the single-evaporator mode is 26.2% to 62.8% higher than that of the dual-evaporator mode, but the effective heating capacity and COP of the dual-evaporator mode are 26.6% to 67.6% and 11.2% to 50.0% higher, respectively. In cold environments, priority should be given to ensuring heating capacity and energy efficiency[51]. Haifeng Lu et al. further developed four dehumidification and reheating modes, achieving dynamic refrigerant flow direction control through solenoid valves and electronic expansion valves, and validated the energy efficiency advantages of mode switching within a wide temperature range of -10°C to 25°C[52].

3.4 Vehicle-Level Integrated Thermal Management System and Coupled Flow Directions Among Multiple Modes

3.4.1 Basic Architecture of Integrated Thermal Management

Independent operation of subsystems inevitably leads to energy waste. The core of integrated thermal management is to build a reconfigurable energy distribution network among the three circuits of battery, electric drive, and air conditioning through valves and heat exchangers, enabling flexible dispatch of heat among multiple heat sources and heat sinks[7].Integrated thermal management consists of two sets of circuits: the refrigerant circuit and the water circuit. The refrigerant circuit includes a compressor, expansion valves, and heat exchangers, relying on compression heating and throttling cooling to move heat. The water circuit uses an aqueous ethylene glycol solution as the medium and distributes heat to various locations via an electronic water pump and multi-way valve assemblies. The two circuits are coupled through a water-cooled condenser and a Chiller; the former releases refrigerant heat to the water circuit, and the latter absorbs heat from the water circuit and transfers it to the refrigerant. This division of labor avoids the long-distance laying of refrigerant pipelines across the vehicle scale.

3.4.2 Multi-Mode Working Strategies

Wang Tianying et al. validated through actual vehicle tests an integrated heat pump system based on a six-way valve; vehicles equipped with a waste heat recovery system reduced energy consumption by 24% and 35% in the first hour at ambient temperatures of -7°C and -18°C, respectively[53]. Liu et al. proposed a three-heat source segmented heating control strategy that calls upon motor waste heat, air-source heat pump, and PTC in priority order, significantly reducing heating energy consumption[54].

3.4.3 Flow Characteristics of Multi-Way Valve Assemblies

The multi-way valve assembly is the core actuator for mode switching. Numerical simulation research by Meng Li et al. revealed that the internal pressure loss of multi-way valves is mainly concentrated in the region where the control shaft and housing connect, where the flow direction changes sharply; the pressure loss has a nonlinear positive correlation with the mass flow rate[55]. Dehong Meng et al. further analyzed the steady-state pressure loss and transient response of multi-way valves under three typical modes—cooling, heating, and waste heat recovery—pointing out that the overall pressure loss is highest under cooling mode[56]. Tesla's Octovalve integrates eight coolant flow ports into a single rotating valve body, completing mode switching through valve core rotation; its electric drive circuit is connected in series with the water-cooled condenser, while the external radiator is independent.

3.4.4 Comparison of Integration Schemes of Different Vehicle Models

The Xiaomi SU7 adopts a dual-mode heat pump architecture, compatible with both direct and indirect air conditioning modes. Under extreme cold conditions, it heats the battery in three stages through electric drive stalling heat generation, compressor heating, and PTC assistance, avoiding the slow temperature rise caused by heating the entire piping in a large circulation mode. The hybrid battery thermal management system proposed by Xu et al. compositely uses phase change material, flame-retardant material insulation layers, and microchannel cold plates, effectively alleviating the temperature non-uniformity problem caused by the direct connection between the battery and the cold plate through aluminum fins[57]. Gao et al., addressing the problem of uneven cooling capacity distribution and cabin-battery thermal coupling in refrigerant direct cooling integrated thermal management systems, proposed a collaborative control strategy based on dual evaporators and variable opening valves[58].The design trade-offs of integrated thermal management are closely related to the positioning of the vehicle platform; Tesla pursues physical integration and light weight, Xiaomi pursues heat source redundancy and heating power, and BYD pursues higher energy efficiency limits by reducing heat exchange layers. The divergence of the three paths indicates that the thermal management system has evolved from an auxiliary temperature control device into the energy dispatch center of the entire vehicle.

IV. RESEARCH ON OPTIMIZATION STRATEGIES FOR THERMAL MANAGEMENT SYSTEMS

4.1 Control Strategy Optimization

The previous chapters have dissected the thermal characteristics, component compositions, and working fluid pathways of the battery, motor and electronic control, and passenger cabin air conditioning, and also compared the different approaches of Tesla, Xiaomi, and BYD in architecture selection. These differences all point to the same question: under the constraints of a given vehicle platform, how to enable the thermal management system to maintain the temperatures of more components within a narrower target range using less energy. Around this direction, researchers have carried out extensive optimization work from several angles, including control strategies, structural design, cooling methods, and working fluid substitution.

On the control strategy side, the number of actuators in the thermal management system has increased significantly with the improvement of integration. A typical integrated thermal management vehicle simultaneously controls the compressor speed, the opening of several electronic expansion valves, the electronic water pump speed, the cooling fan speed, the position of multi-way valves, and the PTC heating power. These actuators are coupled with each other. How to find a set of commands that minimize total energy consumption under multiple constraint conditions has become the core challenge of control optimization. Traditional PID control is implemented based on single-loop feedback, which is simple to realize in engineering. However, its parameter tuning is heavily dependent on specific operating conditions. Once the ambient temperature or battery charge/discharge rate changes significantly, the fixed PID parameters will produce overshoot and oscillation. Research by Zhao Xuming et al. found that a fuzzy PID controller optimized using the Grey Wolf algorithm can stabilize within 200 seconds, with an overshoot not exceeding 1°C[59]. Model predictive control provides a more complete solution approach for multivariable coupled systems: in each control cycle, it first predicts the state trajectory over a future time horizon based on a simplified dynamic model of the system, and then solves a finite-horizon optimization problem. Wang Zhen et al. applied MPC to the water pump speed control of the battery cooling circuit; the battery temperature fluctuation range did not exceed 3°C, and the cumulative water pump energy consumption was reduced by approximately 19.2% compared to traditional PID[60]. Reinforcement learning has also gradually entered the research field of thermal management control. Huang Gan used a Double Deep Q-Network to optimize the energy system of electric vehicles with battery thermal management, achieving at least a 6.7% reduction in energy consumption compared to the fuzzy control strategy under aggressive driving conditions[61]. The advantage of this type of method is that it can learn the optimal strategy by itself through a large amount of simulation data, but the interpretability of the strategy and the safety guarantee under extreme operating conditions are still difficulties in engineering implementation. Ahn and Sun proposed a systematic design framework for heat pump thermal management architectures from a control-oriented perspective, automatically generating and screening feasible topologies using graph theory methods, providing a new tool for the collaborative optimization of control strategies and system architectures[62]. Dongjun Li et al. proposed an integrated power and thermal management strategy based on multi-horizon model predictive control, utilizing real-time information such as ambient temperature and road gradient to proactively optimize battery temperature and vehicle speed, achieving the effects of reducing cooling energy consumption by 14.22% and traction energy consumption by 8.26%[63].

4.2 Structure and Component Optimization

The optimization of structures and components presses down on the irreversible losses in the thermal management system from the hardware level. As the last thermal barrier between the battery and the cooling medium, the flow channel structure of the cold plate has always been the focus of optimization. Traditional straight channels and serpentine channels are always unable to achieve both heat exchange area and pressure drop simultaneously. The topology optimization method provides a new problem-solving approach: taking the lowest average temperature or the minimum pressure drop as the objective within a given design domain, and using the material volume fraction as a constraint, the optimal distribution of channel solids is calculated through iteration. In his research on cold plate topology optimization, Cheng Zhenglin found that the Nusselt number of the optimized cold plate was 48.7% higher than that of the traditional straight channel cold plate, and the pump power consumption was reduced by 35.3%[64]. Zhang Da et al. designed a composite cooling scheme of topology-optimized cold plate plus phase change material plus thermally conductive aluminum for large cylindrical batteries, reducing the average temperature by 9.11% and the temperature standard deviation by 12.51%[65]. Microchannel heat exchangers replace traditional large cross-section channels with micro-fine channels with hydraulic diameters below 1 mm, achieving several times the heat exchange area of conventional heat exchangers in the same volume. Jiang Longhui et al. performed multi-factor optimization on the microchannel parallel flow condenser of an R290 air conditioning system, increasing the heat transfer factor by 14.12% and reducing the resistance factor by 1.86%[66]. Chenglong Wu et al. adopted a three-objective topology optimization method to simultaneously optimize heat transfer efficiency, power consumption, and average temperature, achieving a pressure drop of only 2.84 Pa under the condition of a normalized average temperature of 0.48[67].

4.3 Advanced Cooling Methods

When the heat transfer capacity of the cold plate hits the ceiling under high-rate charging/discharging or extreme high-temperature environments, more aggressive cooling methods enter the engineering field of view. Immersion liquid cooling directly submerges the battery in a dielectric coolant, eliminating the multiple layers of contact thermal resistance between the cold plate and the thermal interface material; the heat transfer coefficient can reach several times that of indirect liquid cooling. Single-phase immersion relies on the sensible heat rise of the coolant to carry away heat; two-phase immersion utilizes the latent heat of phase change when the coolant boils on the cell surface, raising the heat transfer coefficient by another order of magnitude compared to single-phase[68]. Numerical research by Khan et al. shows that an optimized cold plate using R134a refrigerant can control the maximum battery temperature at 38.1°C under 4C discharge[32]. The composite scheme of phase change materials and liquid cooling accounts for a considerable proportion of current research. The basic idea is to use phase change materials to absorb the peak heat of short-duration high thermal loads, while the liquid cooling circuit is responsible for continuously removing heat from the phase change material to help it recover its latent heat reserves. The new composite phase change material developed by Chen Jianhan et al. achieves an enthalpy retention rate of over 98% after 5000 phase change cycles, and can control the maximum battery temperature below

45°C during fast charging[69]. The review by Zhi et al. comprehensively reviewed the research progress of composite thermal management coupling phase change materials with liquid cooling, pointing out that this hybrid cooling method can control the maximum battery temperature below 50°C with a temperature difference within 5°C[70].

4.4 Working Fluid Substitution and Prospective Optimization

The selection of working fluids has a fundamental impact on the energy efficiency upper limit and environmental compliance of heat pump systems. R134a has a global warming potential as high as 1430 and faces pressure for gradual reduction and substitution under the framework of the Kigali Amendment. The advantages of R290 as a natural working fluid have been relatively widely confirmed; it has a GWP of only 3, and both its boiling and condensation heat transfer coefficients are higher than those of R134a. System simulation by Li Hailiang et al. shows that under the same compressor at the same speed, the cooling capacity of the R290 system is approximately 30% higher than that of the R134a system[71]. The R290 dual-core counter-flow series heat exchange architecture proposed by Hua Jingyang et al. increased the cooling capacity by 11.62% under extreme summer conditions of 49°C, with a COP reaching 1.67, and the COP under winter conditions of -20°C was more than 9.5% higher than that of the parallel-flow series scheme[72]. The review by Foliaco and Gullo comprehensively reviewed the application progress of R744-based thermal management systems in electric vehicles, pointing out that the transcritical R744 heat pump has significant advantages in low-temperature heating performance, but system cost and control complexity remain the main obstacles[73].

V. FUTURE CHALLENGES AND DEVELOPMENT DIRECTIONS

5.1 Wide Temperature Range Adaptability

The previous chapters have roughly sorted out the problems that the thermal management system has currently solved and the boundaries still being explored, from principle dissection to optimization strategies. However, from the perspective of technological progress, there are still several unavoidable challenges lying on the road of the thermal management system from good enough to better, and these challenges are intricately interconnected.

Wide temperature range adaptability is a pain point that the entire industry encountered earliest and is also the most difficult to cure. The vehicle-level energy flow simulation by Lu Haifeng et al. provides very intuitive quantitative data: the vehicle energy consumption of a typical pure electric vehicle is 8.43 kWh/100 km at a normal temperature of 23°C, soars to 18.16 kWh/100 km in a low-temperature environment of -7°C, with the proportion of thermal management system energy consumption in total energy consumption suddenly jumping to 43.1%, even greater than the energy consumption share of the drive system itself; at a high temperature of 35°C, this proportion is also 25.5%[74]. Behind these two figures are actually two superimposed forces: at low temperatures, the battery internal resistance increases, and the discharge efficiency itself is declining; at the same time, the heating coefficient of the air-source heat pump also attenuates as the ambient temperature drops, forming a difficult-to-bridge scissors gap between heating demand and energy efficiency supply. The current combination of vapor injection, motor waste heat recovery, and battery pulse self-heating has indeed pushed the effective operating range of the heat pump about ten degrees toward the low-temperature end. However, in the extreme cold zone below -20°C, the superposition of the above methods still cannot fully cover the entire heating demand. There is also a bottleneck on the high-temperature side; when the ambient temperature approaches 50°C, the heat exchange temperature difference between the condenser and the environment is compressed to the limit, and the COP drops sharply as the compressor pressure ratio rises. The study by Yang Tianyang et al. on the adaptability of CO_2 ejectors in the wide temperature range of -30 to 50°C discovered a very tricky fact: a fixed-size ejector designed for high-temperature cooling conditions cannot adapt well when placed in low-temperature heating conditions; the nozzle outlet is either over-expanded or under-expanded, both causing shock wave losses and even making the ejector completely lose its entrainment effect[75]. The comparative study by Lee and Kim also shows that in a cold climate of -10°C, the hybrid heating strategy of heat pump plus PTC is superior to pure PTC or pure heat pump schemes in terms of energy consumption and driving range, but the system complexity increases accordingly[76].

5.2 Autonomous Driving and High-Computing-Power Chip Heat Dissipation

The new demands brought by autonomous driving to thermal management are expanding from mere passenger cabin comfort to the precision heat dissipation of high-computing-power chips. The review by Li Jingyan et al. mentions that the computing power of L4 autonomous driving domain controllers will exceed 1000 TOPS in the future, with chip power consumption in the order of hundreds of watts, and the local heat flux density of a single computing core may exceed 100 W/cm^2. However, the on-board environment imposes strict constraints on heat dissipation space, vibration, and sealing[77]; those efficient heat dissipation schemes commonly used in data centers cannot be directly applied. Microchannel heat dissipation and heat spreading technologies are the visible solutions at present: microchannels at the scale of tens of micrometers are directly fabricated into the chip package substrate, allowing coolant to undergo forced convection inside; the heat transfer coefficient can be an order of magnitude higher than that of traditional cold plate schemes. However, issues such as whether the microchannels will clog, how to ensure the insulation compatibility of the coolant, and how to integrate them with the on-board thermal management circuit are all still in the scheme verification stage, and there is still a long way to go before actual vehicle installation.

5.3 Digital Twin and Full Lifecycle Optimization

Digital twin provides a possible path for the thermal management system to move from one-time calibration to full lifecycle continuous optimization. In his research on digital twin-based air-cooled thermal management of battery packs, Wang Kang achieved real-time dynamic prediction of the battery pack temperature field through a GABP neural network and a sensor data-driven temperature field reconstruction algorithm, controlling the maximum temperature difference within 5°C[78]. Pan Wei also verified in his research on a digital twin-based battery management system that the battery temperature could be stabilized within 40°C under actual vehicle operating conditions[79]. These works have indeed proven in the laboratory environment that the digital twin path is technically feasible. However, for truly large-scale deployment, practical issues such as whether the communication bandwidth is sufficient, whether the accuracy can be maintained after model order reduction, and whether the cost of cloud computing is acceptable have not yet been fully resolved. The review by Dhanasekaran et al. also pointed out from a full lifecycle perspective that the combination of digital twins and intelligent control is an important development direction for the next generation of BTMS[80].

5.4 Environmentally Friendly Working Fluid Switching

The switch to environmentally friendly working fluids is currently moving from regulatory expectation to engineering reality. R134a, with a global warming potential as high as 1430, is being phased down under the framework of the Kigali Amendment, and this is already a certainty. As an alternative working fluid, R290 has a GWP of only 3 and good thermodynamic properties. The appraisal results of the Danfoss VZN series environmentally friendly refrigerant compressors show that the R290 variable frequency scroll compressor can already achieve a high outlet water temperature of 80°C at an ambient temperature of -10°C and 55°C at -25°C without relying on vapor injection or liquid injection[81]. However, the flammability of R290 means that everything from compressor housing strength, pipe joint sealing, to the configuration of leak detection sensors must be redesigned. The safety assessment of coexisting high-voltage electrical systems and flammable refrigerants is not a matter of a single component, but a cross-system engineering problem. The R744 transcritical cycle takes another path, exchanging ultra-high operating pressure for stable low-temperature heating performance and environmental harmlessness, but the high-pressure side pressure exceeding 100 bar requires the compressor and piping to be developed from scratch.

5.5 Multi-Dimensional Technology Integration Trends

These challenges are actually not independent lists of problems, but a complex amalgamation. Wide temperature range adaptability requires changes in the working fluid and cycle architecture of the heat pump system; the switch to environmentally friendly working fluids just provides a window of opportunity for redesign, but the safety design issues brought about by the working fluid change in turn limit the paths that the integrated architecture can take. The heat dissipation demands of autonomous driving have raised the service objects and cooling precision of thermal management to a higher level, while the digital twin provides computing and decision-making tools for managing increasingly complex multi-heat-source systems. In the future, the competitiveness of thermal management systems may no longer depend on breakthroughs in a single technology, but on whether these intersecting dimensions can be integrated into an orderly evolving engineering system.

VI. CONCLUSION

This paper systematically reviews the principles, composition, working paths, and optimization strategies of new energy vehicle thermal management systems within a complete framework from components to the entire vehicle. The heat generation mechanisms, cooling and heating principles, and key components of the three subsystems—battery, motor and electronic control, and cabin air conditioning—are disassembled one by one. The switching of refrigerant and coolant flow directions under different modes runs through the entire narrative as a connecting thread. In terms of technical path selection, Tesla's full coolant-side integration centered on the Octovalve, Xiaomi's platform flexibility achieved through discrete multi-valve body networking, and BYD's system simplification by eliminating intermediate circuits through refrigerant direct-cooling and direct-heating represent three different understandings of integrated thermal management. This also demonstrates that there is no universally optimal architectural design for thermal management systems; rather, it is a system decision tied to the vehicle platform positioning and cost structure.

The review of optimization strategies reveals another layer of fact: the four dimensions of control strategy, structural design, cooling methods, and working fluid substitution are not independent tracks but an interpenetrating technical network. Model predictive control and deep reinforcement learning are pushing thermal management from single-loop regulation to multi-variable collaboration. Topology optimization and microchannel heat exchangers are reducing irreversible losses at the hardware level. Immersion liquid cooling and composite phase change material schemes are expanding the boundaries of heat dissipation capacity under extreme operating conditions. The two natural working fluids, R290 and R744, respond to the tightening of environmental regulations using different thermodynamic paths.

From this, several general judgments can be condensed: The thermal management system is evolving from an auxiliary subsystem into the hub of vehicle energy dispatch. The essence of integration is the redefinition of function levels rather than the simple stacking of components. The core of intelligence lies in predictability and adaptability, not merely staying at the level of temperature feedback. Looking ahead, the substitution of environmentally friendly working fluids has entered the engineering practice stage from technical demonstration. Whichever of R290 and R744 can first find a balance within the triangle constraints of safety, cost, and low-temperature performance will determine the technological landscape of future vehicle-mounted heat pump systems.

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REFERENCES

[1] Kuikui Li, Fanlin Liu, Jie Liu, et al. Research on Range Attenuation Characteristics and Testing Technology of Electric Vehicles under Low Temperature Environment. Special Purpose Vehicle, 2024, (08): 49-52.

[2] Lidong Song. Research on Efficiency Improvement of Indirect Heat Pump Air Conditioning System for Pure Electric Vehicles. Guangxi University of Science and Technology, 2022.

[3] Wurong Huang, Du Li, Bin Li, et al. Brief Analysis on Thermal Safety of Power Batteries for New Energy Vehicles. Automobile Parts, 2025, (03): 7-10.

[4] Xuelian Chen, Cunshan Zhang, Ran An. Battery Thermal Management and Battery Safety Technology. Chinese Journal of Power Sources, 2020, 44(08): 1177-1181.

[5] Ziqi Zhang. Research on Electric Vehicle Heat Pump Air Conditioning System and Energy-Saving Strategies. Shanghai Jiao Tong University, 2018.

[6] Jiong Huang, Yao Chen, Shaojun Gao, et al. Optimization Technology for Winter Range of Pure Electric Vehicles. Auto Time, 2021, (04): 85-86.

[7] Biao Jiang. Analysis on Integration Technology of Air Conditioning and Battery Thermal Management System for New Energy Vehicles. Automobile Knowledge, 2026, 26(01): 4-6.

[8] Ning Wang. Design and Control Strategy of Integrated Thermal Management System for Pure Electric Vehicles. Chongqing University of Technology, 2025.

[9] Ping Ye, Dongjing Xu. Analysis on Thermal Management System Technology of BYD Dolphin. Auto Maintenance & Repair, 2023, (11): 30-33.

[10] Zhiyou Shan. Design and Analysis of Thermal Management System for Pure Electric Vehicles. Harbin Institute of Technology, 2025.

[11] Wenjie Tian, Xiaoyan Song, Chenwei Dong, et al. Research on Battery Thermal Management System of Electric Vehicles. Science and Technology Innovation and Application, 2025, 15(16): 148-151.

[12] Dongjun Li. Research on Electric Drive and Electronic Control Thermal Management System and Waste Heat Recovery System for Pure Electric Vehicles. Chongqing University, 2021.

[13] Xing Chen. Research on Optimization and Energy Saving Benefits of Thermal Management System for New Energy Vehicles. Auto Electric Parts, 2025, (07): 34-35+38.

[14] Mingzhang Pan, Dongliang Hu, Lu Liang, et al. Coordinated thermal–energy management for battery energy storage systems in hybrid electric vehicles. Journal of Energy Storage, 2026, 164.

[15] Rongjiang Tang, Qingqing Wang, Fei Xiao, et al. Performance Optimization of Cooling System for Heavy-Duty Commercial Vehicles. Chinese Hydraulics & Pneumatics, 2020, (05): 96-102.

[16] Ke Liu. Research on Performance of Integrated Thermal Management System for Pure Electric Passenger Vehicles. Beijing Jiaotong University, 2025.

[17] Yiyin Zhang. Simulation and Optimization of Integrated Thermal Management System for Pure Electric Heavy Trucks. Beijing Jiaotong University, 2023.

[18] Jikang Yang. Research on Control Strategy of Thermal Management System for a Pure Electric Vehicle under Low Temperature Conditions. Chongqing Jiaotong University, 2025.

[19] Liange He, Jinwang Tang, Limin Wu, et al. Energy consumption optimization of thermal management system for extended-range electric vehicles based on 11-way valve heat pump architecture. Applied Thermal Engineering, 2026, 289(P1).

[20] Youyou Gao, Xing Xu, Cong Liang, et al. A comprehensive review of thermal management for electric vehicles: Subsystem technologies, integrated architectures, and advanced controls. Journal of Energy Storage, 2026, 151.

[21] Jianfang Dou. Optimization of Power Battery Thermal Management System for BYD Qin EVplus. Auto Pictorial, 2025, (12): 71-73.

[22] Mi Tian. Optimization Design and Performance Improvement of Power Battery Thermal Management System for New Energy Vehicles. Auto Electric Parts, 2026, (03): 33-35.

[23] Cenyu Liu, Runcheng Liu, Xiaowei Leng, et al. Design and Optimization of Temperature Uniformity of Battery in Energy Storage Air-Cooled Cabinet. Optoelectronic Technology Application, 2025, 40(04): 57-62.

[24] Runze Zhang, Tingbo Zhou. Mechanical Structure Optimization Practice of Battery Thermal Management for New Energy Vehicles. Auto Electric Parts, 2026, (05): 30-32.

[25] Kang Chen, Yuchun Cao, Zhaoyong Ren. Design and Optimization of Leaf Vein Bionic Liquid Cooling Plate for Lithium-Ion Batteries. Chinese Journal of Power Sources, 2025, 49(09): 1890-1898.

[26] Longhua Xu. Design and Optimization of Power Battery Heat Dissipation Structure Based on Tesla Valve Liquid Cooling Channel. East China Jiaotong University, 2025.

[27] Xijiao Zhu, Xiaona Ma, Huaxia Yan, et al. Improvement of Temperature Uniformity of Direct Cooling Battery Thermal Management System for Electric Vehicles under Dynamic Conditions. The Chinese Journal of Process Engineering, 2026, 26(04): 427-436.

[28] Zhongcheng Fang, Guoqiang Liu, Gang Yan, et al. Study on superheat control methods for refrigerant direct cooling thermal management systems of electric vehicle power batteries. Applied Thermal Engineering, 2026, 300(P3).

[29] Feifan Zhou, Jinhao Meng, Zihan Zou, et al. Composite Thermal Management of Battery Energy Storage System Based on Liquid Cooling and Phase Change Material. High Voltage Engineering, 2026.

[30] Xu Huang, Yicai Liu, Furui Li, et al. Design of Phase Change Material and Liquid Cooling Hybrid Thermal Management System Based on Multi-Objective Optimization. Journal of Central South University (Science and Technology), 2026.

[31] Chenqing Li, Changqi Zhang, Zhiyu Zhou, et al. Optimal Design of Battery Thermal Management System Coupling Topology-Optimized Liquid Cooling Plate and Phase Change Material. Safety and Environmental Engineering, 2026.

[32] Fuzail Khan, P.M. Sutheesh, R. Ram Kumar, et al. Numerical investigations on battery thermal management system using refrigerant based cold plate. International Communications in Heat and Mass Transfer, 2026, 177.

[33] Lukas Acker, Luis Vincent Fiore, Erik Stenger, et al. Comparing Heating Systems for Degradation-Aware Battery Thermal Management in Electric Minibuses: PTC Heater vs. Heat Pump. Batteries, 2026, 12(4).

[34] Zhilin Hu, Tianqiang Zhang, Fang Yang. Development Trend of Tesla Electric Vehicle Thermal Management Technology. Automotive Digest, 2021, (01): 53-57.

[35] Bofeng Zhang, Xiaohui Bai, Fenglan Wang, et al. Hydraulic Performance Optimization of an Integrated Dual-Effect Chiller for Electric Vehicle Battery Cooling System. International Journal of Automotive Technology, 2026, (prepublish).

[36] Dongmei Wang, Siyi Li, Yanping Liang. Review of Thermal Design and Thermal Management Technology for Drive Motors of New Energy Vehicles. Transactions of China Electrotechnical Society, 2026, 41(02): 389-415.

[37] Vijay Kumar Mahto, Alankrita Singh. Thermal management of an IGBT module utilizing in-built automotive cooling systems. Thermal Science and Engineering Progress, 2026, 72.

[38] Ruke Ni. Thermal Management Design and Analysis of Oil-Cooled Electric Drive System Assembly. Shandong University, 2024.

[39] Waruna Maddumage, Safouene Ouenzerfi, Souad Harmand, et al. Thermal management of hairpin winding traction motors in electric vehicles. Applied Thermal Engineering, 2025, 273.

[40] Youwang Feng. Design and Energy Consumption Optimization of Integrated Thermal Management System for Pure Electric Vehicles Based on Multi-Mode Cooperative Control. Anhui University of Science and Technology, 2025.

[41] Liange He, Zilong Li, Yan Zhang, et al. Design and thermal performance optimization of a spray-heat pipe composite cooling structure for YASA motors. International Communications in Heat and Mass Transfer, 2026, 177.

[42] Liange He, Haodong Jing, Yan Zhang, et al. Performance research of integrated thermal management system for battery electric vehicles with motor waste heat recovery. Journal of Energy Storage, 2024, 84(PB).

[43] Liang Tang, Jingyi Zhang, Ningzhen Wang, et al. Heating Strategy and Energy Consumption Optimization of Motor Waste Heat Recovery for Hybrid Electric Vehicles. Journal of Chongqing University, 2026.

[44] Tianying Wang, Jianlong Li, Zhifang Gong, et al. Analysis of Energy-Saving Potential of Waste Heat Recovery under Low Temperature Conditions for Electric Vehicles. Journal of Refrigeration, 2026, 47(02): 51-60.

[45] Kai Fu, Fan Yang, Shiren Chen, et al. Research on Charging Thermal Management Strategy Based on Motor Stalling. China Auto, 2021, (08): 51-58+64.

[46] Menglong Feng, Xinliang Jin, Longgang Li. Energy Efficiency Optimization of New Energy Vehicle Heat Pump System under Low Temperature Environment. Automobile Knowledge, 2026, 26(05): 10-12.

[47] Mingkang Liu, Lin Su, Yidong Fang, et al. Experimental Study on Low-Temperature Heating Performance of Electric Vehicle Heat Pump System with Vapor Injection. Fluid Machinery, 2021, 49(10): 7-14.

[48] Denghui Liu, Fang Wang, Qiushi Wang, et al. Performance Study of Electronic Expansion Valve in Electric Vehicle Air Conditioning System. Light Industry Machinery, 2020, 38(06): 27-32.

[49] Xiaoyang Gu, Lin Su, Kang Li, et al. Study on Regulation Characteristics of Electronic Expansion Valve for Electric Vehicle Air Conditioning System. Chinese Journal of Low Temperature Physics, 2022, 44(05): 370-376.

[50] Haijun Li, Gang Chen, Zhiyong Su, et al. Effects of electronic expansion valve superheat on refrigeration performance of new vehicle heat pump air conditioning system at high temperatures. Thermal Science, 2025, 29(3A).

[51] Mingfei Tan, Jiayun Hu, Yanming Miao, et al. Research on Dehumidification and Heating Performance of Dual-Evaporator Heat Pump System for Electric Vehicles. Fluid Machinery, 2025, 53(03): 9-16.

[52] Haifeng Lu, Dandong Wang, Junye Shi, et al. Performance and energy implications of a reconfigurable multi-mode dehumidification and

reheating heat pump for electric vehicles. Case Studies in Thermal Engineering, 2026, 80.

[53] Tianying Wang, Jun Wu, Jiawei Wu, et al. Energy consumption analysis and performance evaluation of electric vehicle integrated thermal management system experiments. Applied Thermal Engineering, 2025, 269(PA).

[54] Liu Xiao-Ang, Zhang Fengting, Zhang Zaicheng, et al. A three-heat source segmented heating control strategy based on waste heat recovery technology for electric vehicles. Energy Conversion and Management, 2024, 300.

[55] Meng Li, Siyu Zheng, Mingshan Wei. Flow Loss Analysis and Structural Optimization of Multiway Valves for Integrated Thermal Management Systems in Electric Vehicles. Energies, 2023, 16(13).

[56] Dehong Meng, Xiaoxia Sun, Yongwei Zhai, et al. Flow Loss and Transient Hydrodynamic Analysis of a Multi-Way Valve for Thermal Management Systems in New Energy Vehicles. Energies, 2026, 19(2).

[57] Qiang Xu, Haonan Chui, Yan Xu, et al. A hybrid battery thermal management system with integrated flame retardant material. Applied Thermal Engineering, 2026, 300(P3).

[58] Xue Gao, Qing Gao, Chun Gao, et al. Exergy-informed collaborative control of refrigerant-based integrated thermal management systems for electric vehicles. Thermal Science and Engineering Progress, 2026, 73.

[59] Xuming Zhao, Junwei Jiang, Xin Chen, et al. Optimization of Fuzzy PID Control Strategy for Electric Vehicle Thermal Management System Based on GWO. Small Internal Combustion Engine and Vehicle Technique, 2026, 55(02): 65-74.

[60] Zhen Wang, Shenghua Yao. Model Predictive Control Based Water Pump Control for Battery Thermal Management System. Journal of Hubei University of Automotive Technology, 2026.

[61] Gan Huang. Research on Optimization Strategy of Electric Vehicle Energy System with Battery Thermal Management Based on Reinforcement Learning. Donghua University, 2022.

[62] Changsun Ahn, Jing Sun. Control-oriented design framework for heat pump-based thermal management systems of electric vehicles. Control Engineering Practice, 2026, 172.

[63] Dongjun Li, Qiuhao Hu, Weiran Jiang, et al. Integrated power and thermal management for enhancing energy efficiency and battery life in connected and automated electric vehicles. Applied Energy, 2025, 396.

[64] Zhenglin Cheng. Research on Topology Optimization Design of Liquid Cooling Plate Channel for Lithium-Ion Battery Thermal Management System. Chongqing Jiaotong University, 2024.

[65] Da Zhang, Zican Lin, Yasong Sun, et al. Thermal Management of Large Cylindrical Batteries Using Topology-Optimized Liquid Cooling Plate and Phase Change Material Synergy. Journal of Xi'an Jiaotong University, 2026.

[66] Longhui Jiang, Zeyin He, Jianhui Wang, et al. Structural Design of Microchannel Parallel Flow Condenser for Electric Vehicle Air Conditioning System. Low Temperature and Superconductivity, 2026, 54(04): 51-58.

[67] Chenglong Wu, Qihe Zhao, Long Chang, et al. Research on thermal characteristics of lithium-ion batteries based on cold plate topology optimization and parametric study using RSM and NSGA-II. International Communications in Heat and Mass Transfer, 2026, 177.

[68] Zhenfei Pan, Peifeng Huang, Yimo Luo, et al. Research Progress on Indirect Cold Plate and Immersion Liquid Cooling in Lithium-Ion Battery Thermal Management. Energy Storage Science and Technology, 2026, 15(03): 1023-1038.

[69] Jianhan Chen, Xiangyu Chen, Lingrui Lu. Research on Lithium Battery Thermal Management Design and Thermal Runaway Suppression Based on Composite Phase Change Materials. Battery Industry, 2025, 29(06): 481-487.

[70] Maoyong Zhi, Qinrou Xu, Qiang Sun, et al. A comprehensive review on battery thermal management based on phase change material coupled with liquid cooling. Ionics, 2026, (prepublish).

[71] Hailiang Li, Dong Yang, Weichen Zuo, et al. Study on Operation Characteristics of R290 Replacing R134a in Electric Vehicle Thermal Management System. Refrigeration and Air-Conditioning, 2025, 25(11): 63-68.

[72] Jingyang Hua, Binbin Yu, Li Yu, et al. Research on Novel Vehicle R290 Indirect Thermal Management System and Its Performance. Automotive Engineering, 2025, 47(10): 2037-2048.

[73] Blanca Foliaco, Paride Gullo. Advances and challenges of R744 based thermal management systems in electric vehicles. Discover Vehicles, 2026, 2(1).

[74] Haifeng Lu, Dandong Wang, Junye Shi, et al. Study on Energy Flow Characteristics of Electric Vehicles under Wide Temperature Range Driving Conditions. Drive System Technique, 2026, 40(01): 62-69+78.

[75] Tianyang Yang, Huiming Zou, Hui Zhou, et al. Study on Adaptability of CO2 Ejector under Vehicle Conditions from -30 to 50℃. Automotive Engineering, 2024, 46(04): 682-690.

[76] Yebin Lee, Won Suk Kim, Jaeyoung Han. Comparative study of thermal management systems in electric vehicles: Exergy and energy efficiency under cold climate conditions. Renewable Energy, 2025, 253.

[77] Jingyan Li, Qing Wang, Huai Zheng, et al. Heat Dissipation Challenges and Research Progress of High-Computing-Power Chips for Vehicles. Electro-Mechanical Engineering, 2025, 41(06): 17-23.

[78] Kang Wang. Research on Air-Cooled Thermal Management of Lithium-Ion Battery Pack Based on Digital Twin. Xidian University, 2023.

[79] Wei Pan. Optimization Research of New Energy Vehicle Power Battery Management System Based on Digital Twin. Auto Electric Parts, 2025, (04): 9-11+15.

[80] Anitha Dhanasekaran, Yathavan Subramanian, Minh Thang Le, et al. Battery thermal management systems for electric vehicles: A review of current status, opportunities, and future challenges. Journal of Energy Storage, 2026, 166.

[81] Haiyun Ma, Wenhu Yao, Lin Ma, et al. VZN Series New Environmental Refrigerant Variable Frequency Heat Pump Compressor. Danfoss (Tianjin) Co., Ltd., 2024-09-07.