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Thermal Management Technologies for Power Batteries in New Energy Vehicles

Yutong Dai

Shenyang Ligong University, Shenyang, China
3068808207@qq.com

Abstract. Electric vehicles and large energy storage systems are developing very fast. The heat safety of power batteries is a big problem that stops them from getting better and being used widely. Efficient and reliable thermal management systems are very important to keep batteries working at a good temperature, stop the danger of thermal runaway, and make batteries last longer. This paper gives a full review of the latest research and future development of power battery thermal management technologies. First, based on the basic ideas of power battery technologies, it analyzes the heat problems of new systems like high-energy-density lithium-ion batteries and solid-state batteries, especially the conflict between energy density and safety, as well as problems at low temperatures and heat during fast charging. Second, it fully reviews and compares today's main thermal management and cooling technologies, including air cooling, liquid cooling (indirect and direct contact), phase change material cooling, and biomimetic cooling, and talks about their working rules, structure, good points and bad points in detail. Also, for complex working conditions and many needs, the paper pays attention to the mixed design of hybrid thermal management systems, such as liquid cooling working with phase change materials and heat pipes, and shows better performance and balance among cost, weight and system complexity. Finally, it says that intelligent thermal management is the future, and introduces new research such as using AI and big data to predict and control battery heat, and using digital twin technology to build virtual models for full life battery health management and early warning of thermal runaway. This review wants to give a full theory and technical help for the design and improvement of next-generation battery thermal management systems with high safety and high energy efficiency.

Keywords: new energy vehicles, power batteries, thermal management systems, intelligent control, machine learning

1. Introduction

With the global change in energy use and more electric vehicles, new energy vehicles like electric cars have become very important for sustainable development. As the "heart" of electric vehicles, power batteries decide how far cars can drive, safety, reliability, environment use, and service life [1,2]. Among many things that affect battery work, heat is a key point for performance and safety. Keeping the right temperature is needed for good energy, long life, and safety. If temperature is not

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good or out of control, batteries will become bad fast or even dangerous like thermal runaway [3]. So, good and reliable thermal management systems are very necessary for power battery development and use, especially high-energy-density lithium-ion batteries [4].

Now, power batteries are becoming better with higher energy density, faster charge, and wider temperature use [5,6]. But higher energy density and new materials bring new heat problems. The balance between energy density and safety is more difficult in bad conditions. Also, batteries work worse in low temperatures, so thermal management systems need better heat control and heat keep [7]. Old single cooling ways like air cooling or simple liquid cooling cannot meet the needs of next-generation batteries for good temperature control, high heat dissipation, and light design [4,8-10].

Because of this, battery thermal management research is changing from old passive cooling to active and smart control with multi-physics use. On one hand, new cooling materials and heat structures like phase change materials, microchannels, and biomimetic designs appear. Hybrid use like liquid cooling with phase change materials makes performance better [11-13]. On the other hand, with AI, big data, and computer simulation, thermal management control changes from "passive answer" to "active predict and control". By building high-fidelity digital twin models and using machine learning to predict and control battery heat, we can know battery health and warn thermal runaway early in the whole life. This makes batteries safer, cheaper, and longer life [14].

This paper gives a full review of latest research and future trends in power battery thermal management. Chapter 2 first shows main and new battery principles and performance, and analyzes key heat problems to know thermal management needs. Chapter 3 studies main thermal management ways including air cooling, liquid cooling, phase change material cooling, and biomimetic cooling, talking about their rules, structure, good and bad points, and improvement directions. Chapter 4 focuses on system mix and smart optimization, analyzing hybrid thermal management good points and problems, and AI and digital twin use for smart and predictive thermal management. Finally, Chapter 5 summarizes the paper and shows future directions and key research. By reviewing existing technologies and new ideas, this paper wants to give useful help for innovation and engineering use of power battery thermal management technologies.

2. Power battery technologies: principles, evolution, and challenges

2.1. Principles and performance comparison of mainstream battery technologies

With advances in industrial technology, materials science, and applied chemistry, lithium-ion batteries—owing to their low weight, high capacity, good charge retention, high operating voltage, and environmental friendliness—have become the most widely used power batteries in pure electric vehicles and are currently regarded as the optimal energy supply for such vehicles.

The operating principle of lithium-ion batteries is based on the movement of lithium ions between the cathode and anode materials. Figure 1 shows the working principle of a lithium-ion battery. During charging, electricity from an external power source makes lithium ions leave the cathode material, move through the electrolyte, and enter the anode material. Electrons flow from the cathode to the anode through the external circuit to keep charge balance. During discharge, lithium ions leave the anode and move back to the cathode through the electrolyte, while electrons flow from the anode to the cathode via the external circuit, producing an electric current to power external devices [15].

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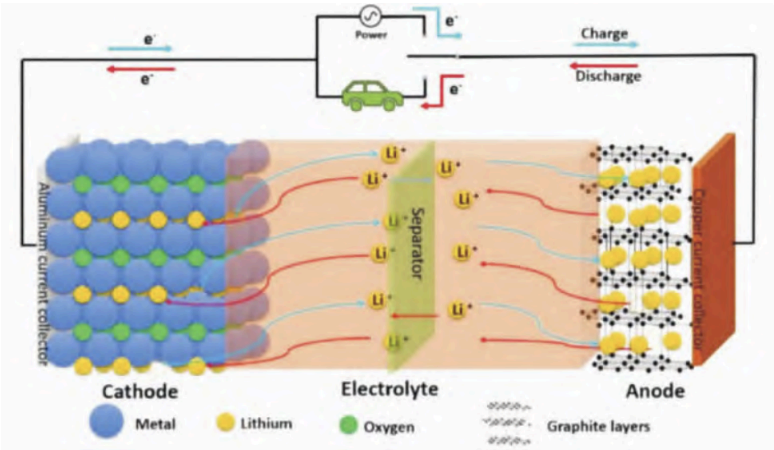

Figure 1. Schematic diagram of the working principle of a lithium-ion battery [1]

Currently, the new energy vehicle market is mainly using ternary lithium batteries and lithium iron phosphate (LFP) batteries. They work well together in performance and cost.

Ternary lithium batteries use lithium nickel manganese cobalt oxide (NCM) or lithium nickel cobalt aluminum oxide (NCA) as the cathode material. NCM batteries usually have an energy density of about 150–220 Wh/kg and a cycle life of 800–4000 cycles. NCA batteries have an energy density of about 200–260 Wh/kg and a cycle life of 150–1500 cycles. Because their energy density is relatively high, ternary lithium batteries are widely used in mid-to-high-end cars that need long driving range [2]. Demiröz Gökhan et al. [16] compared NCM ternary lithium batteries and LFP batteries in vehicles. They found that under the same WLTP driving conditions, NCM batteries gave about 9% higher power than LFP batteries. However, ternary lithium batteries have worse thermal stability. Their thermal runaway temperature when fully charged is usually 150 to 250 °C. So they need complex thermal management systems (such as liquid cooling or air cooling) to reduce thermal runaway risks. Also, higher prices of key materials like cobalt and nickel make ternary lithium batteries more expensive, which is bad for their market share [5].

Lithium iron phosphate batteries use $LiFePO_4$ (LFP) as the cathode material. Their energy density is 150–200 Wh/kg and cycle life is 2000–6000 cycles. Although their energy density is lower than ternary lithium batteries, LFP batteries cost much less (about 20%–30% lower) and are much safer. Their thermal runaway temperature is higher than 250 °C. These make LFP batteries the best choice for commercial vehicles that need high reliability and safety [6]. In recent years, as people worry more about the safety and cost of ternary lithium batteries, more passenger cars also start to use LFP batteries.

Solid-state batteries use solid electrolytes instead of traditional liquid electrolytes. As a new battery technology, solid-state batteries have many advantages that traditional liquid-electrolyte batteries do not have. They have high energy density, long life, better safety, and wide working temperature range. All these show strong application potential [17]. With further development in materials science, manufacturing processes, and cost control, solid-state batteries are expected to be widely used in the future and help the new energy vehicle industry develop quickly.

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2.2. Current core technical challenges

2.2.1. The inherent trade-off between energy density and safety

At present, as the energy density of lithium batteries increases, safety problems have become more serious, and thermal runaway is the most important problem. Thermal runaway in lithium batteries means the temperature inside the battery rises quickly and cannot be controlled, because of many exothermic reactions happening one after another. It is mainly caused by three kinds of abuse: mechanical abuse, electrical abuse, and thermal abuse [3]. As new energy vehicles are used more widely and more often, the number of lithium battery thermal runaway accidents goes up every year. These accidents are very dangerous to people's lives and property, and they make it harder to popularize new energy vehicles.

Ternary lithium batteries, which are often used in passenger cars, once had a leading position because they have relatively high energy density. But their safety is not as good as their market share. The cathode materials of ternary lithium batteries are very active, so thermal runaway can happen at relatively low temperatures, and they release a lot of heat [9]. In comparison, lithium iron phosphate batteries are usually safer, because the $LiFePO_4$ cathode material needs higher energy to break down and is not easy to decompose. However, their energy density is limited and cannot match ternary lithium batteries. Also, under the same working conditions, LFP batteries produce a little more heat than ternary lithium batteries, so they also need good thermal management [16].

In addition, increasing battery capacity is another common way to make pure electric cars drive longer. But bigger battery packs greatly increase the risk of thermal runaway caused by battery problems, such as internal short circuits or separator failure. Besides, car lithium batteries are usually sealed, so they cannot lose heat very well. And heat is surely produced inside when charging and discharging. As battery packs become bigger, more heat is produced, so heat is easier to build up, and the risk of thermal runaway becomes even higher.

2.2.2. Thermal management under low-temperature performance degradation

One big problem of lithium batteries is that their performance becomes much worse in low temperatures, not as good as the theoretical values. When the ambient temperature gets lower, the electrolyte becomes thicker, and the solid electrolyte interphase inside the battery is less permeable. This directly stops lithium ions from moving well between the electrodes, makes electrochemical reactions much slower, and increases internal resistance. Also, when you charge lithium batteries in low temperatures, lithium ions cannot enter the graphite anode easily. This makes metallic lithium stick to the surface and form lithium dendrites. This process makes the battery's capacity smaller and increases the risk of internal short circuits [7]. Mainstream Battery Thermal Management Cooling Technologies and Current Status

3. Mainstream battery thermal management cooling technologies and current status

3.1. Air cooling

Air cooling uses air to take away heat. It is the oldest way of thermal management. Air cooling has two types: passive and active. Passive cooling only puts the heat-generating parts in a cooler place, and heat is exchanged by natural air flow. So its cooling ability is very weak. Active air cooling, also called forced convection cooling, uses fans to drive air flow, which makes heat transfer faster. Active air cooling makes heat dissipation better to some extent. Because it is not very expensive, it is

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widely used in new energy vehicles. It can control the battery's temperature basically. Now, research on air cooling mainly focuses on two things. First, optimize air flow—for example, change the shape of the air inlet or add flow deflectors to make heat transfer more efficient. Second, optimize the layout of the battery pack by adjusting the space between each battery cell, so that the temperature of the whole battery pack is more uniform.

Air has low specific heat capacity and poor thermal conductivity. These two points limit how good air cooling systems can be. So air cooling can no longer meet the needs of modern new energy vehicles with high-voltage platforms. This is especially true when the vehicles are charged/discharged at high rates, or when they need high performance and long driving range. Therefore, air cooling is more often used as an auxiliary method together with other advanced thermal management technologies. For example, it is placed around liquid cooling systems to make the coolant release heat to the surrounding air faster. Tian et al. [18] designed a hybrid battery thermal management system that combines air cooling and liquid cooling. In this system, air cooling is an auxiliary heat dissipation method. It uses fans to drive air flow, which further improves the liquid coolant's ability to take away heat. This method balances heat transfer performance and energy consumption well, and keeps the temperature difference of the battery within 4 °C during the whole discharge process.

3.2. Liquid cooling

Liquid cooling uses liquid to take away extra heat from battery packs. Liquid coolants can transfer heat much better than air. So liquid cooling is more efficient than air cooling. That's why it has become the first choice for battery thermal management systems in most new energy vehicles.

Liquid cooling has several types, such as immersion cooling, microchannel heat sinks, jet impingement cooling, thermoelectric cooling, and embedded cooling. Immersion liquid cooling means putting the battery pack directly into the coolant. Heat is transferred from the battery to the liquid to be dissipated. Because the battery pack is fully covered by the coolant, this way makes the temperature very uniform. But its heat transfer efficiency depends on how fast the coolant flows. The coolant needs to be electrically insulated, have high thermal conductivity, and not corrode things. Also, this way has high requirements for battery sealing [8].

Microchannel heat sinks (MCHSs) are made by precision micromachining. They have small channels (diameters from about 1 μm to 1000 μm) on silicon or metal substrates. When liquid coolant flows through these channels, heat is taken away well—either directly in liquid form or by phase change. Since it was invented in the 1980s, MCHSs have quickly become a high-performance cooling method for electronic parts. They are small and transfer heat well. With the development of new energy vehicle technologies, modern car battery thermal management systems prefer small and efficient MCHS radiators. Practical studies show that no matter what the battery is like, MCHS technology can reduce battery temperature, improve performance, and make batteries last longer. A big problem of MCHS technology is that small channels are easy to be blocked by dirt in the coolant. This can make thermal performance and system reliability worse [11].

Jet impingement cooling works by pushing coolant through narrow jet holes. High-speed coolant jets hit the surface of the part that needs cooling, so heat is taken away. Because the jet hits and slows down in the stagnation area, very thin hydrodynamic and thermal boundary layers form near the surface. This greatly improves local heat transfer. So jet impingement cooling is widely used in places with high heat fluxes. Research on jet impingement cooling mainly focuses on optimizing nozzle design and array layouts, and improving heat dissipation efficiency by using heat transfer areas better [11,19].

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Thermoelectric cooling, also called semiconductor refrigeration, works on this principle: when direct current is applied to thermoelectric materials, P-type and N-type semiconductors in the thermoelectric module form thermocouples (P–N junctions). Under the electric field, electrons and holes move in a certain direction. They absorb heat on one side of the module and release it on the other side. Thermoelectric cooling has many special advantages: it does not need refrigerants; it has no mechanical parts, so there is no noise, vibration, or mechanical wear; it has low thermal inertia and responds quickly; thermoelectric elements are easy to make small; and cooling capacity can be controlled precisely. However, its efficiency is relatively low, manufacturing and processing are complex, and costs are high. These problems still limit its large-scale use [20].

3.3. Phase change material cooling

Phase change material (PCM) cooling is a thermal management technology. It uses the heat absorbed or released when the heat transfer medium changes phase to stabilize the temperature of lithium batteries. It does not need extra energy. Figure 2 shows how PCM cooling is used for cylindrical lithium-ion battery thermal management. When the battery pack generates heat during charging and discharging, the PCM medium absorbs the heat well. This makes the temperature of the battery pack more uniform. When the ambient temperature is lower than the battery pack's normal working temperature, the PCM releases the stored heat and sends it back to the batteries. This special two-way temperature control ability allows PCM systems to improve battery performance in low-temperature conditions [9].

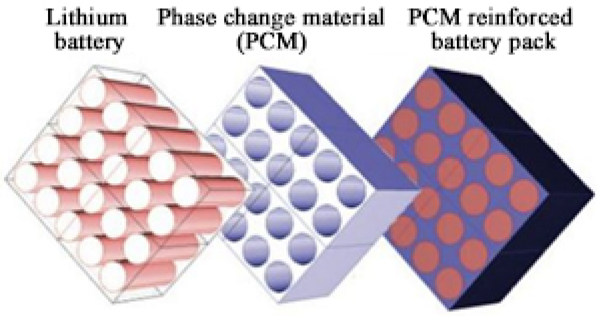

Figure 2. Schematic diagram of phase change material cooling [10]

PCMs can be divided into two main types: solid–liquid phase change materials and liquid–gas/vapor phase change materials. Among them, solid–liquid PCMs change volume very little when they change phase. So they are more mature and reliable. They are the most widely used type in current PCM cooling systems. Solid–liquid PCMs include materials like paraffin waxes, fatty acids, and hydrated salts. Compared with inorganic PCMs, organic PCMs (such as fatty acids) are usually more chemically stable. They have lower supercooling, higher cycling efficiency, lower cost, and are less likely to have phase separation. So they have broader application prospects. However, these materials usually have low thermal conductivity. This limits their use in battery thermal management systems [11].

Improving the thermal conductivity of PCMs has become a key research focus in phase change thermal management systems. Two main methods have been put forward. The first is to add high-thermal-conductivity materials (such as carbon-based or metallic materials) into the PCM [20]. The second is to put metallic fins or metal foams into the PCM to make heat transfer faster [19]. Temesgen Abera Takiso et al. [4] analyzed the development of PCM cooling technologies. They

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concluded that PCM systems using only one medium cannot effectively control the maximum battery temperature and the temperature uniformity between individual batteries. On the other hand, hybrid PCM media with high-thermal-conductivity additives can better improve the overall performance of thermal management systems.

It is hard to quickly release the extra heat stored in PCMs only by natural convection. So there is a risk of thermal saturation. For this reason, PCMs are often used together with other active cooling methods. For example, adding forced air cooling devices or liquid cooling systems around the PCM, or putting heat pipes into the PCM. All these are effective ways to improve PCM's thermal conductivity and heat dissipation ability [9].

In addition, PCM leakage after melting is a big problem for its wide use. A common way to solve this is to use porous materials (such as expanded graphite, silicon-based porous ceramics, or aluminum nitride skeletal structures) to absorb the PCM and improve its shape stability. Another way is to microencapsulate the PCM. Paraffin is wrapped in chemically stable shell materials to stop the liquid from flowing out of the microcapsules. However, research in this field is still in the early stage. Many problems need to be solved before it can be widely used in practice [21].

3.4. Biomimetic cooling

In recent years, with the development of biomimetics and interdisciplinary integration, many heat exchanger designs get ideas from natural phenomena. There are already some practical uses of biomimetic technologies in thermal management. Figure 3 shows some typical biomimetic cooling structures. Numerical simulations and experimental studies show that these bio-inspired structures can dissipate heat much better than traditional geometric structures.

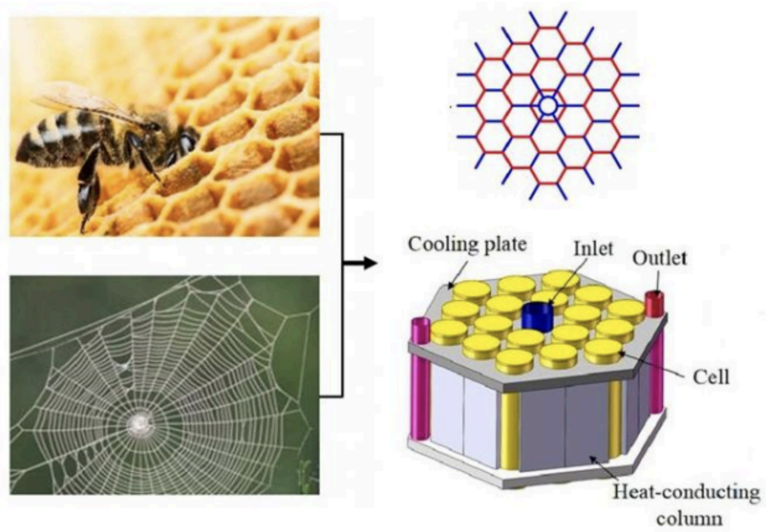

Figure 3. Cold plate heat sink inspired by honeycomb and spider web structures [22]

Liu Fen et al. [23] got ideas from the efficient water transport and cooling ways of leaf venation networks in plants. They proposed a new phase change cooling medium flow channel. It is based on topology optimization and imitates leaf vein structures. Experimental results showed that, compared with traditional rectangular structures, the leaf vein–shaped heat sink can reduce the temperature of lithium iron phosphate batteries by 34.6% more. And the maximum surface temperature difference is reduced by 40.3%. Zeng Zhixin et al. [24] developed a liquid cooling thermal management system for power batteries. It is inspired by lung alveoli. In this design, the coolant microchannels copy the

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capillary network of alveoli. This increases the heat transfer area between the coolant and the batteries, and improves temperature uniformity. After optimizing the structure, the system can keep the maximum battery temperature in an ideal range. There is almost no temperature difference between individual batteries.

At present, most biomimetic cooling technologies are still in the research stage. The main reason that limits their industrial use is the complex shape of biomimetic structures. This makes manufacturing more difficult and more expensive. So it prevents them from being used on a large scale in practice.

4. Frontiers in system integration and intelligent optimization

4.1. Hybrid thermal management systems: from "single" to "synergistic" approaches

4.1.1. Advantages of typical hybrid configurations (liquid cooling + PCM, liquid cooling + heat pipes/MCHS)

With the rapid growth and widespread use of new energy vehicles, the volume, capacity, operating voltage, and current of power battery packs have kept increasing. This makes the need for efficient and reliable thermal management technologies more and more urgent. Single-mode thermal management systems cannot meet the growing heat dissipation needs of modern battery packs. So hybrid thermal management systems, which combine many mature and main thermal management technologies, are gradually becoming a new development direction for battery thermal management in new energy vehicles. Typical hybrid systems now being studied include liquid cooling combined with air cooling, air cooling combined with phase change material (PCM) cooling, and liquid cooling or microchannel heat sink (MCHS) systems combined with PCM.

Liquid cooling makes up for the weak points of air cooling, such as low specific heat capacity of air and poor heat transfer efficiency. At the same time, adding air-cooling devices to liquid cooling systems can improve heat transfer at the end of the coolant circulation loop, help the flow field develop fully, and make the overall temperature more uniform. Zhong Ziqi et al. [12] built a numerical model of a hybrid liquid–air cooling thermal management system and studied the temperature characteristics of a battery pack to test its cooling performance. The results showed that the system could keep the maximum temperature below 313.15 K and the temperature difference less than 5 K. It showed better thermal performance than single-mode thermal management systems.

Thermal management systems combining air cooling and PCM appeared quite early. PCM-based cooling gives good temperature uniformity, while air cooling is better than PCM when the environment temperature is high. However, air cooling usually has poor temperature uniformity, and this problem becomes worse when the inlet air speed is low [13]. By combining these two methods, we can use their advantages and make up for their weaknesses. But its cooling effect is still not as good as liquid coolants. The main advantages of air cooling combined with PCM are simpler structure and lower cost.

Because liquid has much higher specific heat capacity and heat transfer ability than air, it can take away the heat stored in PCM more quickly and avoid thermal saturation. So hybrid cooling systems combining PCM and liquid cooling are an important development direction in battery thermal management technologies. Compared with traditional metal liquid cooling plates, hybrid liquid cooling plates with PCM inside are lighter. They can greatly reduce the energy used to drive coolant circulation and make temperature uniformity better [14]. In addition, combining liquid cooling with PCM can reduce the amount of coolant and PCM materials needed. Combining PCM with MCHS is

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another hybrid thermal management solution. It is more efficient than traditional methods. In such systems, PCM is close to MCHS, and the heat from the battery is absorbed by both PCM and the microchannel heat sink. Because MCHS systems need lower flow speed than traditional liquid cooling plates with big channels, the power they use is lower. Importantly, hybrid thermal management systems combining PCM and MCHS can keep temperatures stable under extreme working conditions—such as local thermal abuse of single cells—and stop thermal runaway from spreading to the whole battery pack. This greatly improves overall battery safety [11].

4.1.2. Complexity and trade-off challenges in integrated design (performance, cost, and weight)

Hybrid thermal management systems are a major development trend in battery thermal management for new energy vehicles. However, they cannot be used in all situations. Compared with passive or single-mode cooling methods, hybrid cooling systems are usually bigger and heavier. They have more complex structure and control, use more energy, and respond more slowly. Therefore, we must choose the right thermal management strategy according to specific working conditions and heat dissipation needs. For example, in low ambient temperature, we may prefer to reduce the use of active cooling systems. In applications that need high stability of battery output performance, PCM-based hybrid thermal management systems may be more suitable.

4.2. Intelligent control and predictive management: from "passive response" to "active intervention"

4.2.1. AI and data-driven approaches (machine learning–based battery thermal behavior prediction and optimization control)

With the continuous improvement of onboard sensor accuracy and enhanced edge computing capabilities, data-driven methods are increasingly used in battery thermal management systems. This has created a new framework based on machine learning, focusing on temperature prediction and cooling strategy optimization. Compared with traditional methods, machine learning has great advantages in modeling flexibility, environmental adaptability, and real-time inference speed. It has broad application potential in key tasks such as battery thermal state modeling, anomaly detection, and closed-loop control. When closely combined with actual working scenarios, machine learning can make system scheduling more flexible and efficient in complex, dynamic, multi-task environments, and greatly improve overall battery thermal management performance.

Battery thermal management strategies must balance temperature control, energy consumption optimization, and dynamic response performance. Optimizing control strategies can achieve lower temperature deviation, better temperature uniformity, less auxiliary energy consumption, and faster regulation time. Traditional proportional–integral–derivative (PID) control methods have simple structure and low delay, so they are suitable for steady-state operations and cost-sensitive platforms. Model predictive control (MPC) can balance temperature precision and energy efficiency under limits, but it depends heavily on model accuracy and computing ability. Data-driven and intelligent optimization strategies have better prediction ability and adaptability to working conditions, but they need comprehensive training to control generalization errors. Reinforcement learning has strong potential in solving complex nonlinear and multi-objective coordination problems, but it needs high training and validation costs. In practice, hybrid methods are often used. For example, during fast charging, climbing, or highly variable working conditions, a "data-driven prediction + traditional

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control" framework can be used. Intelligent algorithms based on data-driven models do high-level strategy search, while traditional PID or MPC does real-time low-level control [14].

4.2.2. Digital twin technology (high-fidelity virtual models for lifecycle health management and thermal runaway prediction)

Battery thermal state modeling and prediction aim to estimate the temperature of individual cells and battery packs using sensor data, and predict future temperature trends to support preemptive thermal management strategies. The complex physicochemical characteristics of batteries, together with highly variable working conditions, put high demands on model responsiveness and generalization ability.

Machine learning can use a lot of historical data to effectively predict battery thermal states without needing precise physical models. It has become an important tool to overcome the limitations of traditional methods. Deep learning models are especially good at capturing complex nonlinear relationships, long-term dependencies, and spatial features. Supervised learning can model nonlinear relationships with high accuracy and adaptability. Unsupervised and semi-supervised methods are suitable for large-scale online data processing and anomaly detection [14].

In practice, model selection and deployment should consider the characteristics of each training method and its suitability for the task. For stable data distributions and long control cycles (such as calibration scenarios), supervised learning and lightweight models can provide stable predictions. In fast charging, high-load, rapid acceleration, or extreme climate conditions, deep learning combined with physics-informed models can capture complex thermal processes more accurately. It supports high-precision prediction, extrapolation, real-time system scheduling, and thermal runaway warnings. For fleet operations and long-term health management, unsupervised and semi-supervised methods are good at large-scale online data processing and anomaly detection. In situations with limited onboard computing power, lightweight networks and embedded implementations can meet real-time state estimation needs. A hierarchical and collaborative combination of multiple model types balances prediction accuracy, real-time performance, and computing load. It provides a strong foundation for control strategy design and practical engineering applications.

5. Conclusions and outlook

5.1. Research summary

The development of thermal management technologies for new energy vehicle (NEV) batteries has always been closely connected with the development of battery technologies. Early passive solutions, mainly air cooling, had clear cost advantages. They were good for battery systems with low energy density and low charge–discharge rates. But these methods cannot meet the high thermal management needs of modern NEVs anymore. Now they are mainly used as auxiliary methods in new thermal management solutions. With higher energy density and fast-charging needs, liquid cooling has become the mainstream because it can transfer heat very well. System design has changed from simple cooling to precise temperature control. In recent years, people have actively studied microchannel cooling, phase change materials (PCM), heat pipes, and direct cooling. These technologies aim to achieve better temperature uniformity, safety, and energy efficiency. Each method has its own good points and limits. People are increasingly combining them with liquid cooling to form hybrid systems, so that the total heat dissipation performance is as good as possible. Overall, battery thermal management has changed from a simple temperature control function into a

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complex, integrated engineering system. It deeply combines electrochemistry, materials science, thermofluid dynamics, and intelligent control. Its main goal is to make battery performance as good as possible while keeping safety and long life.

5.2. Future outlook

5.2.1. Materials innovation: development of, high-thermal-conductivity materials

Materials innovation will be very important to solve current thermal management performance problems. Key research directions include: 1) High-performance phase change materials (PCM): Develop composite PCMs with high latent heat, adjustable thermal conductivity, low supercooling, and long cycle stability. Also solve problems of encapsulation and volume change. 2) Advanced thermal conductive materials: Use high-thermal-conductivity fillers such as graphene and carbon nanotubes in thermal greases, pads, and composites to improve interfacial heat transfer efficiency. 3) Multifunctional materials: Develop integrated materials that have thermal insulation, flame retardancy, structural support, or stress-sensing functions. This can make system design simpler. 4) Materials for solid-state batteries: Develop interface-compatible materials with high thermal conductivity and heat-blocking ability. These materials will solve the local overheating and interface contact problems of solid-state batteries.

5.2.2. System architecture innovation: toward lightweight, modular, and highly integrated thermal designs

Battery thermal management systems (BTMS) will connect more closely with the whole vehicle structure. Main trends include: 1) High integration and structural design: Develop cell-to-chassis designs. They combine battery pack housing and cooling plates into one structure. This can greatly reduce weight and save space. 2) Modularization and standardization: Develop flexible, standardized thermal management modules. They can fit different vehicle types and battery types. This reduces R&D and manufacturing costs. 3) Multi-heat-source coordinated management: Combine battery, motor, electronic control, and cabin thermal management systems. This optimizes energy flow and realizes whole-vehicle thermal management. It can use waste heat efficiently, especially to improve driving range in cold weather.

5.2.3. Deepened intelligence: achieving all-weather, full-condition adaptive, high-precision thermal management

Intelligent BTMS will change from "sense-and-control" to "predict-and-adapt". Key research focuses include: 1) Advanced state estimation and thermal modeling: Use electrochemical-thermal coupled models, data-driven models, or hybrid methods. They can estimate and predict internal battery temperature, heat generation rate, and thermal runaway risk in real time. 2) Multivariable coordinated control strategies: Develop multi-objective optimization algorithms. They consider temperature, aging, working conditions, environment, and user behavior. They can control cooling/heating strength, flow rate, and distribution adaptively and precisely. 3) Digital twin and cloud-edge collaboration: Build digital twins for battery thermal management. Use cloud big data to train models and optimize strategies. Use vehicle-cloud cooperation to improve full-lifecycle thermal performance.

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5.2.4. Sustainability: lifecycle carbon footprint and recyclability of thermal management systems

Under the "dual carbon" goals, the environmental influence of BTMS is becoming more important. Future research should focus on: 1) Full lifecycle assessment: Study energy use and carbon emissions from material extraction, manufacturing, use, to recycling. Find key ways to reduce them. 2) Eco-friendly media and low-carbon processes: Use cooling media with low global warming potential. Study system adaptability. Develop manufacturing processes with less greenhouse gas emissions. 3) Design for repairability and recyclability: In the design phase, make parts (such as cold plates, pipes, pumps/valves) easy to disassemble and recycle. This helps recover important materials like aluminum, copper, and coolant. It supports circular economy.

In summary, the future of NEV battery thermal management will be a process of continuous innovation driven by multiple subjects and goals. Only through breakthroughs and deep integration in materials, system structure, intelligence, and sustainability can next-generation thermal management systems be realized. They will be safer, more efficient, smarter, and more environmentally friendly. This will build a solid foundation for the sustainable development of the NEV industry.

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