Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA29636

Advances in Electric Vehicles Thermal Management Technology

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Abstract. Developing electric vehicles (EVs) offers an effective solution to the challenges of carbon emissions and carbon neutrality facing society today. Thermal management technology for electric vehicles is emerging as a key focus area within the academic community. To aid future research, in this paper, some of the latest advancements in thermal management technologies of electric vehicles were reviewed, including battery cooling systems integrating microchannel cooling plates, heat pipes, and heat pumps, along with the latest applications of phase change materials in battery cooling. Finally, the challenges facing thermal management technology of electric vehicles in the future were summarized, and this paper offers some outlooks. Efficient thermal management technology not only directly determines the driving range and safety of electric vehicles but also serves as a core guarantee for their large-scale commercial application. Therefore, in-depth exploration and optimization of thermal management systems are of great strategic significance for achieving sustainable development of the electric vehicle industry and low-carbon transformation in the transportation sector. This paper aims to provide a meaningful reference for the development and research of novel thermal management technologies for electric vehicles.

Keywords: Electric Vehicles, Thermal Management, Lithium-ion Battery

1. Introduction

In modern society, electric vehicles occupy an important position in advancing sustainable development, achieving carbon peak and carbon neutrality, and enhancing the quality of human life, offering considerable economic value and social benefits. To enhance the performance of electric vehicles and further expand their market share, advancements in related technologies are indispensable. Electric vehicles are complex thermal systems, which means thermal management for electric vehicles is inherently challenging. Thermal management refers to the effective control and regulation of heat within systems, equipment, or environments through a series of technical methods, ensuring their operation within safe and efficient temperature ranges. Its main target is to optimize the generation, transfer, storage, and dissipation of heat, and enhancing system performance, reliability, and energy efficiency while preventing failures or damage caused by overheating or excessive cooling. Optimizing thermal management can further enhance the performance, safety, lifespan, and user experience, making it one of the core issues in the technological development of the electric vehicles.

To date, numerous review papers have summarized and outlined thermal management technologies for electric vehicles, reflecting the significant progress and research in this field. Hwang et al. reviewed the heat generation mechanisms in lithium-ion battery cells and the current research efforts on four primary thermal management approaches in battery: air-cooling systems, liquid-cooling systems, phase-change material (PCM)-based systems, and thermoelectric-based systems [1]. Additionally, this study reviews the advantages and disadvantages of each battery thermal management type. Wang et al. highlighted the latest advancements in various thermal management technologies in their paper, including air cooling and liquid cooling for stators, windings, and rotors [2]. Concurrently, the paper highlights conduction-based heat transfer enhancement methods utilizing potting compounds, thermal pastes, thermal conductors, phase change materials, and heat pipes. Subsequently, it explores hybrid thermal management techniques designed to address extreme operating conditions. Zhang et al. introduced common methods of thermal management for lithium-ion batteries, discussed their advantages while comparing their disadvantages, and provided an outlook on future developments [3]. Malik et al. reviewed the systems of battery thermal management for pure electric vehicles and hybrid power vehicles. The paper explains the cooling strategies employed in various thermal management systems [4]. Additionally, the application of phase change materials in thermal management systems and related issues were reviewed. Antti et al. conducted a general review of thermal management systems for electric vehicle cabins. Various thermal modeling techniques for vehicle cabin and important concepts related to thermal comfort of cabin is discussed in this paper. Different solutions of technical and operational methods for thermal management of cabin under high temperature and low temperature conditions were evaluated [5]. The latest research achievements in improving thermal management efficiency were analyzed, including passive thermal management, thermal system control, heat pumps, and cabin pre-conditioning. This paper focuses on the latest developments in thermal management technology for electric vehicle batteries, primarily covering research advances in new equipment, new components, new materials, and other related areas. This paper is expected to provide valuable insights for future research and development in electric vehicle battery thermal management technology.

2. Small-scale cooling devices

In modern thermal management, cooling plates and heat pipes play a crucial role, particularly in high-power or compact systems such as electronic devices and energy systems. Electric vehicles are also a key application scenario for these components. The cooling plate operates by utilizing channels made of metal or composite materials to facilitate forced convection heat transfer with a liquid coolant. The operating principle of heat pipes relies on phase-change heat transfer, for instance, evaporation-condensation cycles and capillary structures, to achieve ultra-high thermal conductivity. These devices significantly enhance system reliability and performance through efficient heat transfer and temperature homogenization.

2.1. Streamlined channel cooling plate

Typically, to meet power requirements, battery packs consist of up to several thousands of battery cells in electric vehicles. These battery cells can be assembled into multiple battery modules. Multiple cooling plates are equipped with these battery modules to manage thermal conditions.

Because the battery is rectangular in shape, the gaps between batteries are filled with these cooling plates. Controlling the temperature and flow rate of the mass of liquid to monitor and regulate the internal temperature of the module. Microchannel cooling plate thermal management systems demonstrate excellent cooling efficiency in regulating battery pack temperatures. A dual-channel cooling plate alone can maintain peak temperatures below 40°C for over half of the discharge duration. The more of channels, the higher the cooling efficiency [6]. However, traditional straight-channel cooling plates also suffer from drawbacks such as high flow resistance, high pump power requirements, uneven flow distribution, and susceptibility to clogging.

In 2019, Huang et al. proposed a novel approach to improve the overall cooling performance of lithium-ion battery by introducing streamlined concepts into multi-microchannel cooling plates. Numerical simulation models were investigated, and the computational results of traditional plates with straight-channel and compared streamlined channel cooling plates with the former. Research on multi-microchannel cooling plates was conducted from multiple perspectives, including pressure difference, temperature difference, and uniformity [7]. The results indicate that employing a streamlined channel model can effectively regulate flow to a smooth state, preventing vortices and shock waves, while the use of streamlined channel plates reduces overall flow resistance. The streamlined channel cooling plate exhibits significantly higher overall performance than typical straight-channel models. For a typical model with straight-channel, the flow resistance within even-channel plates is always greater than that within odd-channel plates. In four and six typical straight-channel plates, the pressure drop reaches as high as 6581 Pa and 6043 Pa when the mass flow rate is 0.005 kg/s. When using a streamlined channel, the maximum measured pressure drop was only 3877 Pa. Streamlined channels effectively decrease pressure drop. They can also effectively avoid direct current surges. In even-channel cooling plates, the aforementioned effect is particularly pronounced. The difference of temperature in different streamlined channel models is comparable to that in typical straight-through channel models, meaning streamlined channel models can maintain the same cooling capacity as typical straight-through channel models. By incorporating streamlined concepts into microchannel cooling plates, the impact of varying channel counts on cooling capacity can be controlled.

2.2. Lithium-ion battery thermal management system with heat pipes

When lithium-ion batteries operate at excessively high power levels, localized micro-regions within the battery reach a threshold temperature. This triggers the onset of material breakdown, making thermal runaway more likely to occur. These processes generate significant additional heat. Temperature affects the process of breakdown, and the breakdown process increases exponentially with rising temperature. Once the process of breakdown begins, battery energy will be released explosively. Numerous factors—such as overheating, excessive discharge, or even internal short circuits, all of these factors have the possibility to cause the overheating. Moreover, in the battery pack, thermal runaway in even one only single cell may rapidly spread and affect nearby cells. These potential risk factors are detrimental to the series operation of lithium-ion batteries, thereby limiting improvements in electric vehicle performance [8].

For thermal management, heat pipes are a highly flexible and effective system. They are readily used as heat exchangers, such as refrigerators, heat pumps (vapor compression or adsorption), and other types of equipment. Heat pipes exhibit higher heat transfer coefficients in condenser and evaporator regions and lower thermal resistance, thereby enabling reductions in heat exchanger area and mass.

In 2021, Alihosseine et al. selected a portion of a battery pack, which consists of batteries and heat pipes made by himself, and conducted experimental studies on its performance [9]. These tests were conducted in a custom-built test chamber capable of precise temperature control, under various ambient temperatures. Additionally, researchers utilized software to establish a model which based on heat pipes to simulate the cooling of battery and compared it with experimental data.

Research findings indicate that to lithium-ion batteries, the temperature of environment is a critical factor influencing its thermal performance. It can influence the surface temperature of the battery and also plays a positive role in achieving uniformity in distribution of temperature.

At environment temperatures of 33°C, 28°C, and 18°C, the average surface temperature of the battery increases by 2°C, 5°C, and 8°C, respectively. Since heat pipes generally have low thermal resistance, combined with forced convection in the condenser section, the system can maintain the battery temperature in its optimal range. During battery operation under dynamic conditions and continuous cycles of charge-discharge, the surface temperature can be maintained within the ideal range through the heat pipes. Without heat pipes, after ten cycles, the battery surface temperature rose to nearly 45°C. This proves the fact that heat pipes is an effective equipment for battery thermal management. Additionally, while adding heat pipes increases the weight of battery by approximately 10%, it significantly enhances the battery's efficiency and service life. The importance of heat pipes in battery packs is even more pronounced, as they connect the cells together to generate greater electrical power.

2.3. Integrated thermal management system combining High-Pressure Heat Exchanger (HPHE) with heat pump air conditioning

Heat pumps utilize thermal energy from low-temperature heat sources, by consuming a small amount of electrical energy, heat can be transferred to the environment with high temperature, or vice versa. Their coefficient of performance (COP) is typically greater than 1. Currently, heat pumps in widespread use come in various models and can be broadly categorized into two types: one of them requires external mechanical work, while the external thermal energy is needed by another one. Heat pump systems provide an economical alternative for various applications: industry, commerce, resident, and so on, capable of recovering heat from different sources. With energy costs continuing to rise, saving energy and improving overall energy efficiency have become imperative. Due to their significant energy-saving potential, in energy recovery systems, heat pumps have become more significant [10]. Improving the reliability and performance of heat pumps has become a persistent concern of researchers.

Zou et al. proposed a thermal management system in 2016. The system couples a heat pump with cooling and preheating of battery based on a standard five-seat electric vehicle [11]. The system uses R134a as refrigerant and operates within a temperature range of -20 °C ~45 °C. This heat pump system consists of the following key components: outdoor heat exchanger, variable-frequency scroll compressor, refrigerant valves, water-gas separator, condenser and expansion valve (cabinet heating), refrigerant-air evaporator (cabinet cooling), and refrigerant-water evaporator (referred to as the battery cooler). Refrigerant-air evaporators and condensers are installed within the ventilation ductwork. The system switches from RV to heating or cooling. Another feature of this battery system is the inclusion of a water-air heat exchanger. This allows the system to cool the battery using natural cold sources and preheat it with positive temperature coefficient (PTC) heaters during colder temperatures. One HPHE could be seen between the battery packs, referred to here as the battery heat exchanger box.

Zou et al. researched the heating and cooling performance of this system. They also investigated the performance of heat transfer of the high-pressure heat exchanger. Research findings indicate that this system is an effective thermal management solution for electric vehicles. The battery pack's specific heat capacity was measured to be approximately 1.24 kJ/kg·°C. There is a delay in heat transfer initiation for the high-pressure heat exchanger in cooling mode, with a startup temperature difference of approximately 7–8°C across its two ends. Under different cooling conditions, the heat transfer performance of heat pipes is approximately 0.87 W/°C. Coolant temperature significantly impacts the performance of heat transfer of high-pressure heat exchangers. When the coolant temperature exceeds 8°C, heat transfer efficiency rapidly increases to a higher value before gradually rising to a relatively stable value of approximately 1.11 W/°C. Since heat pipes can utilize gravitational force during preheating conditions while working, their heat transfer performance is superior to that under heating conditions. Research findings indicate that the performance of heat transfer of high-pressure heat exchangers can meet the control requirements of battery temperature under various operating conditions. In practical applications, to determine the design parameters of the coolant system, computational methods based on the performance of heat transfer of the high-pressure heat exchanger and the specific heat capacity of the battery pack is an effective way.

3. Phase Change Materials (PCM)

The characteristic of PCM is that they can absorb or release a large amount of latent heat while maintaining a nearly constant temperature during the phase transition process. This high latent heat characteristic enables it to maintain a large amount of thermal energy with relatively small mass, significantly improving thermal management efficiency. PCM also exhibits temperature stability, maintaining a constant temperature near its phase transition point to prevent drastic temperature fluctuations. This makes it suitable for scenarios requiring precise temperature control, such as battery and motor thermal management, preventing thermal runaway in systems and extending their lifespan. Additionally, PCM possesses a high energy density, and its application in thermal management facilitates lightweight and compact system designs. In summary, PCM plays a significant role in electric vehicle thermal management. This significance is primarily manifested through its ability to regulate temperature via heat-absorbing or heat-releasing phase change processes (such as solid-liquid or liquid-gas transitions). This addresses a series of key challenges in electric vehicles, including internal thermal energy storage, suppression of temperature fluctuations, and enhancement of energy efficiency.

3.1. PCM combined with fin structure for lithium-ion battery cooling

Fins are common design features for enhancing heat dissipation efficiency. Fin-and-tube heat exchangers have long been utilized for heat exchange between single-phase or two-phase gases and liquids. Its core function lies in improving heat transfer efficiency by increasing the surface area of heat dissipation and optimizing airflow organization. By expanding the surface area, fins can significantly increase the contact area with air or other fluids, thereby enhancing heat dissipation capabilities. By rationally designing the shape, and spacing of fins, the fluid flow state can be optimized, enhancing the convective heat transfer coefficient to achieve heat transfer optimization. However, the limitation of fins lies in the need to reserve sufficient installation space for the equipment, and the heat transfer coefficient of air-side is significantly lower than the heat transfer coefficient of refrigerant-side. Consequently, air-side heat transfer resistance can significantly limit the finned tube heat exchangers' performance [12].

In 2022, Chen et al. successfully enhanced the cooling performance of lithium-ion batteries by utilizing PCM combined with fin structures to improve thermal conductivity during the cooling process [13]. Immerse a cylindrical battery into a chamber filled with PCM. After that, on the battery, place several fins of identical length in order to determine the optimal PCM chamber dimensions and fin count to decrease the maximum battery temperature during the process of discharge.

Research findings indicate that under air-cooling conditions, battery temperature initially rises sharply. One hour later, heat transfer within the battery reaches equilibrium, and the temperature remains nearly constant. However, the rate of temperature rising is different under passive cooling. PCM cooling outperforms air cooling when the PCM has not melted completely. Within the range of natural convection, the maximum cell temperature remains largely unchanged when the convection coefficient varies. However, the maximum temperature of battery will decrease significantly under forced convection. The finding indicates that around the battery, installing fins and inducing the airflow turbulence significantly enhances the cooling performance of phase change materials. Compared to un-finned batteries, finned batteries exhibit higher performance in passive cooling across various fin configurations.

3.2. PCM-based reliable Battery Thermal Management System (BTMS)

Generally speaking, a battery system consists of numerous individual cells to meet voltage and power requirements. An efficient battery thermal management system is necessary to manage a large number of battery cells while achieve best performance under different working conditions. It also helps the battery system maintain thermal limits and improve energy management. Functionally, the battery thermal management system is critically important because it protects the battery from operating under hazardous conditions such as overcurrent, overvoltage/undervoltage, and overtemperature/undertemperature [14]. A large amount of latent heat can be absorbed by PCM during its melting. At the same time, PCM can maintain the temperature near its melting temperature for a period. Due to its unique properties, PCM-based BTMS systems have garnered significant attention and exploration in recent years.

In 2023, Khan et al. outlined the impact of temperature on the performance of lithium-ion battery and the need for reliable thermal management systems for battery in their research. They provided mathematical models for these systems and conducted experimental tests to evaluate the efficiency of this system [15]. This study focuses on hybrid BTMS that combine PCM with different cooling technologies or methods.

PCM-based BTMS offers exceptional value in numerous aspects. Through structural design and integration with novel fin-based, air-cooling, liquid-cooling, HP, TEC, and other heat dissipation technologies, the performance of PCM modules' secondary heat dissipation can be effectively enhanced. The strategy of PCM cooling must be employed in conjunction with optimized heat sinks for secondary heat dissipation. For the purpose of ensuring the battery can work under extreme conditions, this is important. Additionally, integrating PCM into the BTMS can significantly reduce vibration-caused temperature rise, as it reduces vibration waves and prevents them from impacting the battery cells. Research indicates that low-amplitude vibrations hold potential for enhancing the thermal conductivity of composite PCM and reducing battery operating temperatures. Therefore, as future research explores the vibration effects on PCM, researchers may have the chance to develop more precise systems to overcome the temperature issues caused by vibration.

3.3. New embedded PCM Liquid-Cooling Plate (LCP)

Although PCM can be used for efficient passive cooling technology in BTMS, the primary issue hindering its application is its low thermal conductivity. After complete melting, if the heat accumulated in the PCM cannot dissipate promptly, the rising of battery temperature will not stop, leading to BTMS failure [16]. Therefore, active liquid cooling cold plates and passive phase change materials are combined into hybrid liquid cooling systems, offer an efficient solution for addressing thermal management challenges in batteries of lithium-ion.

In 2021, Akbarzadeh et al. presented a novel LCP embedded with PCM for thermal management of electric vehicle batteries [17]. This cooling plate combines the advantages of both active (liquid) and passive (PCM) cooling methods, hence it is referred to as a “hybrid cooling plate.” The hybrid LCP is 36% lighter than the traditional aluminum LCP of the same volume. Beyond cooling capabilities, it also provides heating solutions to mitigate temperature loss during battery cold shutdown.

Research on cooling performance under actual driving cycles indicates that hybrid cooling plates shorten the operational time of liquid cooling, and reduce pump energy consumption. Compared to aluminum cooling plates, the hybrid cooling plate achieves approximately 30% higher cooling efficiency at a flow rate of 1 L/min, thereby enabling increased specific energy in electric vehicle batteries. For example, for a cooling plate with an ambient temperature of 0°C and a heat transfer coefficient $h = 5\ \mathrm{W/(m^2 \cdot K)}$, after a time period of $t = 5345$ s, the temperature at the contact surface between the battery module and the cooling plate in the hybrid cooling plate exceeds 24.5°C, while the temperature in the aluminum cooling plate is approximately 5.5°C. Therefore, hybrid cooling plates can reduce the need for active battery heating in cold environments by keeping the battery warm during short-term parking conditions.

4. Current challenges and future outlook

Currently, the development and application of thermal management technology for electric vehicles still face numerous challenges. First, traditional working fluids such as water cannot meet the demands of all scenarios, performing poorly under extreme conditions like high temperatures and pressures. Second, most organic PCMs currently exhibit relatively low thermal conductivity, resulting in slow heat charging/discharging rates. The phase change temperature range of existing PCMs is extremely limited, making it difficult to meet specialized requirements. Organic PCMs are easily to leak during solid-liquid phase transitions, potentially corroding equipment or contaminating the environment.

Traditional heat pipes rely on passive heat transfer. Its future developments will require integrating variable thermal conductivity technology to enable on-demand thermal conductivity adjustment. Additionally, high-temperature stability solutions for novel low-toxicity, high-thermal-conductivity working fluids (such as ionic liquids and nanofluids) or metallic working fluids (such as lithium and cesium) must be developed. To achieve large-scale, low-cost application of PCM in electric vehicle thermal management, it is necessary to optimize its thermal conductivity, enhance its stability, and develop more advanced encapsulation techniques.

5. Conclusion

This paper provides a comprehensive review and discussion of the latest technologies of thermal management for electric vehicle batteries. Overall, theoretical models provide a reliable and cost-effective approach for analyzing battery temperature distribution, while experimental studies validate numerous thermal management techniques and optimization strategies. This paper analyzes heat pipe cooling technology and PCM cooling technology for lithium-ion batteries, which can better meet the thermal management requirements of electric vehicle batteries. By integrating lithium-ion batteries with microchannel cooling plates, heat pipes, heat pumps, or employing PCM materials for cooling instead of traditional air cooling, the refinement of electric vehicle thermal management technology can be achieved. This approach significantly reduces the difficulty of enhancing electric vehicle performance and safety.

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