BATTERY COOLING SYSTEMS OF ELECTRIC VECHILES

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Abstract
To enhance electric vehicle battery performance, the Battery Thermal Management System (BTMs) plays a crucial role by regulating internal battery temperature within optimal limits. Among the key components, the cooling system is paramount in maintaining this temperature range. Various cooling techniques such as Air Cooling (AC), Liquid Cooling (LC), Refrigerant Direct Cooling (RDC), Phase Change Material (PCM) based systems, Thermoelectric Cooling (TC), Heat Pipe Cooling (HPC), and Hybrid Cooling (HC) have been employed in electric vehicles. This paper provides an exhaustive review of these cooling systems, delineating their respective merits and demerits. The findings offer valuable insights for researchers delving into electric vehicle battery cooling technology.

Keywords: Electric vehicle, battery, cooling system, thermal management system.

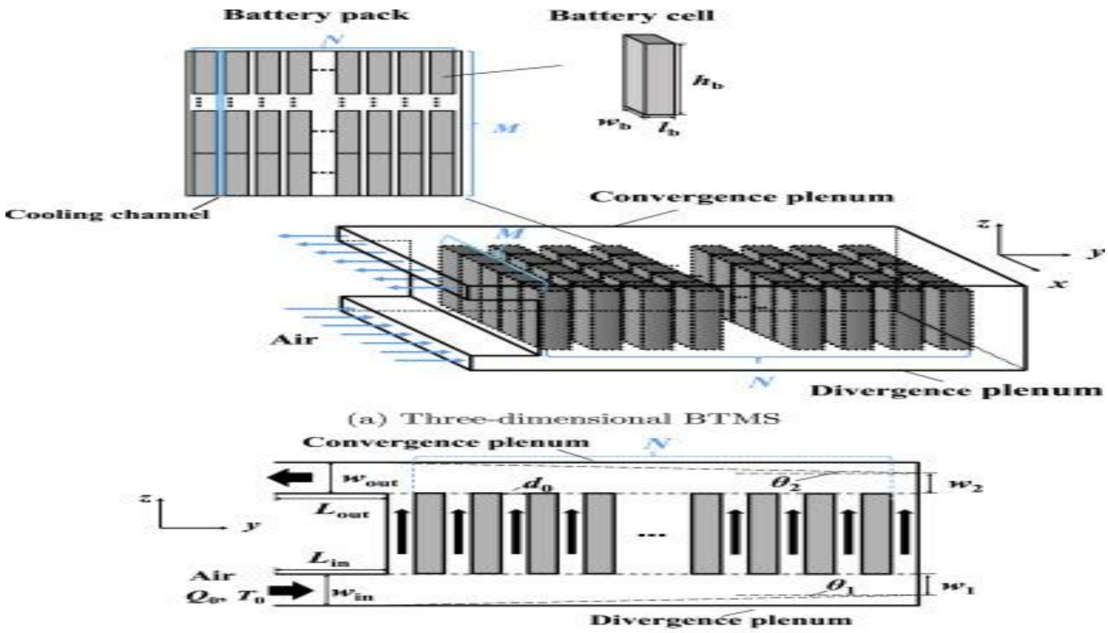
I. INTRODUCTION

In the imminent urban landscape, electric vehicles are poised to supplant their traditional counterparts. Intensive research efforts have targeted the refinement of various technological facets of electric vehicles, encompassing battery technology, energy systems, electric propulsion, safety mechanisms, and comfort features. Among these, battery technology stands as a linchpin, pivotal in advancing electric vehicle technology. Within this domain, ensuring energy storage and thermal safety emerges as paramount concerns. Consequently, battery thermal management becomes a critical frontier demanding meticulous attention to fortify the robustness of electric vehicle design. The pursuit of safer and more enduring battery cells resilient to thermal stresses underscores foundational research endeavours. Furthermore, the design of battery packs assumes significance in mitigating the risks of thermal events, averting potential explosions, or minimizing consequential losses in such occurrences. Optimal battery packing designs are instrumental in sustaining battery cell temperatures within the optimal operational range, typically spanning 25–40°C, with a maximal temperature differential of 5°C across individual cells, thus constituting the optimal working conditions. Addressing the fundamental challenges of Battery Thermal Management Systems (BTMSs) in electric vehicles, this discourse encapsulates a broad spectrum of inquiries. A comprehensive review discerns and categorizes extant and prospective battery management systems, offering a glimpse into the future trajectory of BTMSs for automotive applications. In the realm of cooling systems for electric vehicles, several methodologies are prevalent. Air Cooling (AC), distinguished by its simplicity, affordability, electrical safety, and lightweight nature, presents a compelling solution. Nonetheless, it grapples with limitations in meeting the demands of high-temperature environments or batteries necessitating substantial cooling capacities and enduring charge-discharge cycles. To surmount these constraints, forced-air convection cooling methods leverage cooling fans, airflow management, and specialized fin structures. Liquid Cooling (LC) systems offer a sophisticated approach, facilitating thermal analysis through the development of thermal models and innovative pack designs. Notably, advancements in liquid cooling encompass dynamic systems capable of adapting to changing contact surfaces, ensuring a conducive operating environment for batteries. Refrigerant Direct Cooling (RDC) emerges as a promising avenue for synergistic control of battery thermal safety, particularly in emergencies. A concerted effort towards developing cross-coupling control strategies augurs well for enhancing safety and operational efficiency. Meanwhile, the exploration of diverse refrigerants underscores a concerted push towards environmental sustainability without compromising performance. The utilization of Phase Change Materials (PCM) in cooling systems embodies an area of active research. Combining active liquid cooling with PCM matrices enhances cooling efficacy, while innovative composite PCM materials exhibit promising results in tempering temperature fluctuations during battery discharge processes. Thermoelectric Cooling (TC) harnesses the Peltier effect to regulate heat flux, offering a viable solution for battery thermal management. Coupled with forced convection mechanisms, thermoelectric generators present an effective cooling strategy. Moreover, Heat Pipe Cooling (HPC) emerges as a pragmatic solution, facilitating the integration of BTMSs into the market landscape. Noteworthy applications include electric-thermal coupling models, showcasing the efficiency of heat pipes in optimizing battery performance. Hybrid Cooling (HC) methodologies epitomize a fusion of diverse cooling techniques, capitalizing on the strengths of individual systems while mitigating their inherent limitations. Through mixed cooling approaches, researchers aim to achieve optimal battery thermal management, balancing performance and efficiency considerations. In summary, the convergence of innovative cooling technologies underscores a concerted effort to refine battery thermal management in electric vehicles, ensuring their reliability, safety, and longevity in diverse operating conditions.

II. BATTERY COOLING SYSTEMS

A. Air cooling

The efficacy of air-cooling strategies was investigated through various configurations, altering the relative positions of airflow inlet and outlet to optimize cooling performance. Results demonstrate that positioning inlet and outlet on opposing sides yields superior cooling compared to collocating them, with the inclusion of baffle plates significantly enhancing thermal performance. Simulation results. Modules outfitted with forced-air cooling systems underwent charging at 1 C-rate and discharging at 1, 1.5, and 2 C-rates over three cycles per test. Refinements in the air-cooled BTMS design, particularly in flow pattern optimization, led to enhanced cooling efficiency. An optimization strategy was proposed to optimize inlet and outlet region positions, resulting in a reduction of maximum cell temperature difference by 1.7 K and a 12% decrease in power consumption compared to symmetrical systems. Natural convection in battery cooling systems offers simplicity, cost-effectiveness, and reliance on the natural dissipation process. However, it suffers from uncontrollable wind forces. In contrast, forced convection, while more reliable and easier to maintain, exhibits uneven temperature distribution within the battery. The inherent limitations of air, including its cooling effectiveness, underscore the advantages and drawbacks of air-cooled thermal management. Benefits include operational safety and reliability, minimal material requirements, ease of implementation, and efficient ventilation during the generation of harmful gases.

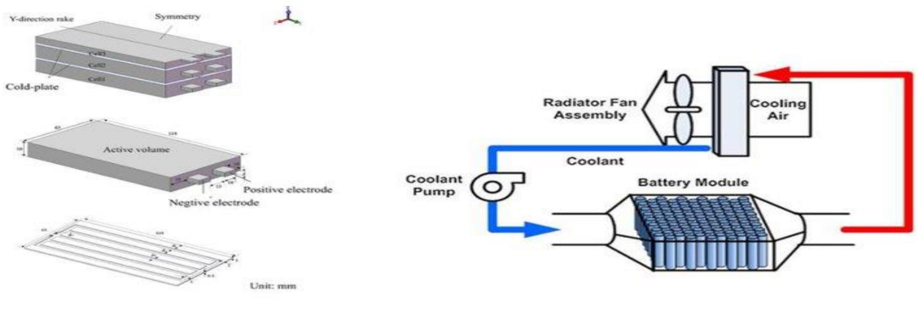


(a) Three-dimensional BTMS

(a) Side view of the BTMS

B. Liquid cooling

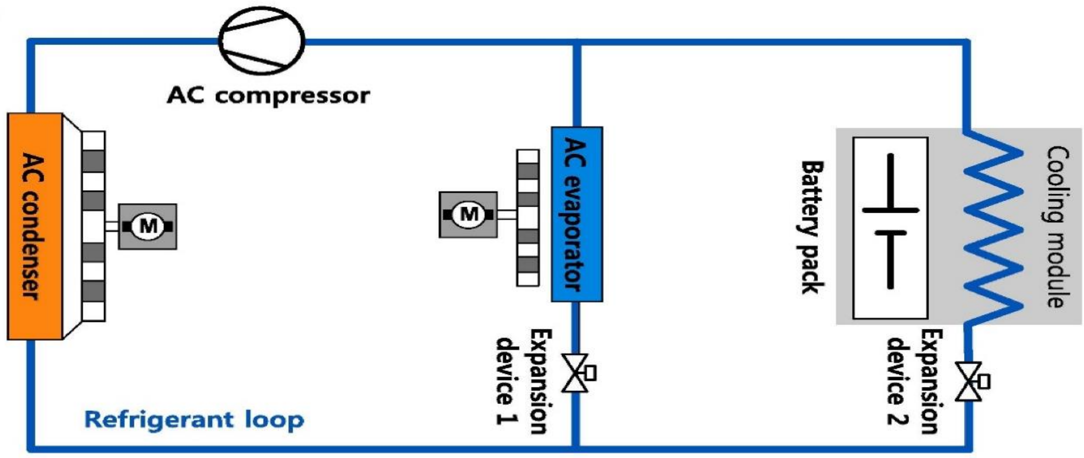
Liquid cooling stands out as a potent method for maintaining battery temperature within optimal ranges. Introducing a novel modular liquid-cooled system for batteries, researchers conducted numerical simulations and experiments to investigate the impact of coolant flow rate and cooling mode on battery module thermal behaviour. The modular structure, conducive to industrial batch production, facilitates flexible battery grouping to align with actual demands, offering fresh insights for liquid-cooled battery thermal management system design. In another study, a liquid cooling-based thermal management system tailored for cylindrical lithium-ion battery modules with variable contact surfaces was devised. Through simulation, the effects of aluminium block length and velocity on thermal performance were examined, contributing to advancements in liquid cooling system optimization. Furthermore, an innovative proposal surfaced, advocating for the use of liquid metal as a coolant for battery pack thermal management. While liquid-cooled battery cooling systems demonstrate efficacy in reducing working temperature and local temperature differences, they entail challenges such as complex system structures, considerable mass, liquid leakage risks, and demanding maintenance. However, in electric vehicle thermal management systems where stringent battery operating conditions are paramount, liquid-cooled systems offer distinct advantages over air-cooled counterparts.



(a) (b)

C. Refrigerant direct cooling

The refrigerant direct cooling system encompasses either a vapor compression or an absorption mechanism. Employing a novel discrete model rooted in electro-thermal coupling and thermal resistance networks, researchers analysed the local temperature control performance of refrigerant direct cooling and liquid cooling systems under real operating conditions. Results underscored the substantial influence of refrigerant phase changes on temperature control efficacy. Proposing a thermal management system (TMS) leveraging R134a refrigerant, researchers employed one-dimensional mathematical simulations to assess various working modes, including battery preheating, mixed heating, and low-temperature mixed heating modes. Notably, investigations into the typical applications of direct cooling in electric vehicles are underway, with ongoing efforts to synthesize research outcomes in the battery cooling domain. Introducing a novel direct two-phase refrigerant cooling approach, researchers sought to enhance performance over conventional liquid cooling for electric vehicle traction batteries. The two-phase refrigerant cooling demonstrated adherence to maximum cell temperature limits even in harsh environmental conditions, yielding a 16.1% increase in battery capacity and a 15.0% reduction in internal resistance compared to liquid cooling. Refrigerant direct cooling offers structural simplicity, effectively reducing the weight of BTMS and enhancing the energy density and economy of the power system. Boiling heat transfer inherent in refrigerant direct cooling confers notable advantages in handling higher heat fluxes through evaporation.



D. Phase Change Material

A phase change material (PCM) serves as a substance capable of releasing or absorbing sufficient energy during phase transition, thereby facilitating effective heat management. Ideal for thermal management solutions, PCMs have garnered attention for their potential applications in electric vehicle (EV) battery cooling systems. Prior efforts have focused on augmenting PCM efficiency within these systems. Explorations into enhancing the thermal conductivity of PCM-44, a eutectic mixture comprising Mg (NO3)2•6H2O, MgCl2•6H2O, and NH4NO3, through the integration of carbon fibres have been conducted. Additionally, proposals have been made for integrating PCMs into Li-ion batteries for EV and scooter applications, accompanied by thermal characterization analyses of Li-ion battery modules. A novel design featuring commercially available high-power Li-ion batteries (HPPC 18650) coupled with a PCM thermal management system has been posited as an alternative to NiMH batteries. The physical state of PCM undergoes transitions with changes in temperature. Despite a narrow temperature range during phase change, PCMs exhibit significant latent heat absorption or release. Noteworthy advantages include minimal volume change, substantial latent heat capacity, and inherent stability. However, PCM cooling performance experiences a notable decline beyond its melting point, limiting its efficacy under extreme temperatures.

E. Thermoelectric Cooling

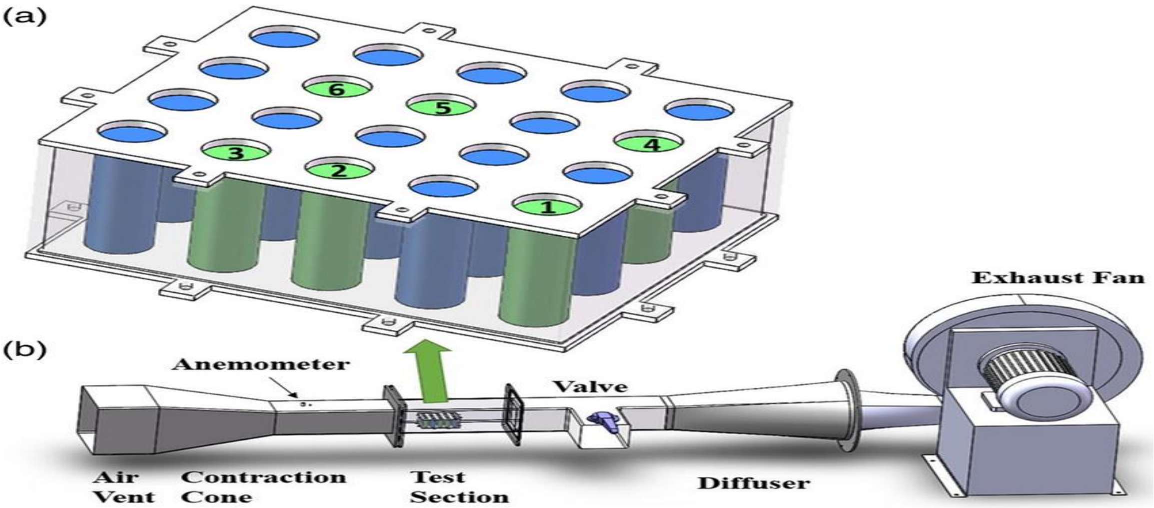
Thermoelectric cooling (TEC) stands as a promising technology poised to transform conventional cooling methodologies. An experimental inquiry delved into an advanced battery thermal management system tailored for emerging electric vehicles, leveraging thermoelectric cooling. Results from experimental tests showcased a substantial reduction in battery surface temperature, plummeting by 43°C (from 55°C to 12°C) with the implementation of a TEC-based water-cooling system for a single cell equipped with a copper holder. This effect was observed under a power supply of 40 V to the heater and 12 V to the TEC module. Furthermore, a comprehensive 3D thermal model was developed to scrutinize the performance of a thermal management system for a lithium-ion battery pack, incorporating TEC components. Simulation models elucidating TEC technology underscore its numerous advantages over conventional vapor-compression cooling systems. While TEC offers compelling advantages, including quiet operation and enhanced system reliability, its widespread adoption is impeded by notable drawbacks. High cost and low energy efficiency remain significant limitations, constraining its application to scenarios prioritizing energy availability, system reliability, and noise reduction over cost efficiency.

F. Heat Pipe Cooling

Heat pipes (HP) represent highly efficient heat exchange components that leverage phase changes in the medium within the pipe to absorb and release heat. A novel heat pipe and wet cooling integrated Battery Thermal Management (BTM) system was developed to manage thermal surges in lithium-ion batteries during high-rate operations. This system's cooling efficacy was evaluated and compared with four other BTM systems incorporating heat pipes, as well as a natural convection cooling method. Temperature collection points, ranging from T1 to T6 for pack-level temperature gradients. A numerical model was constructed and validated to assess the efficiency of the new design. Comparative analysis with traditional air cooling revealed superior maximum temperature control with the proposed design, with maximum temperatures recorded at 16.93°C, 26.07°C, and 36.27°C for 1C, 2C, and 3C discharges, respectively. Furthermore, a battery thermal management system employing heat pipes was established, and a series of battery discharge experiments were conducted under various conditions using offline parameter identification methods. Results indicated that adjusting refrigerant temperature achieved enhanced thermal management effectiveness under suitable ambient temperature conditions. Heat pipes have emerged as integral components in battery cooling systems for electronic equipment, attributed to their exceptional heat flux variability, thermal conductivity, density variability, reversibility of heat flow direction, consistent temperature thermal performance, and environmental adaptability. While offering robust heat transfer capacity, it's imperative to note that heat pipes possess limitations, and their heat load cannot be infinitely increased, despite their superior performance compared to other battery cooling systems

G. Hybrid Cooling

Hybrid cooling, integrating multiple cooling systems, has emerged as an energy-efficient solution for electric vehicle (EV) batteries. A novel coupled thermal management system combining phase change material (PCM) and liquid pipe was proposed and numerically investigated for a prismatic $LiFePO_4$ battery pack. Study findings demonstrated effective cooling performance, maintaining maximum temperature and temperature differences within acceptable limits even at an ambient temperature of 45°C. Additionally, a Hybrid Thermal Management System (HTMS) employing PCM and six flat heat pipes was devised to sustain temperature profiles below 40°C under high current rates. Results showcased the robust cooling capabilities of HTMS, with a significant reduction in temperature compared to natural convection and heat pipe systems. Further innovations include a hybrid system combining PCM with forced-air cooling, analysed through numerical and experimental methods. Moreover, a circulating-cooling BTMS utilizing R134a with frequency conversion control was implemented to assess its thermal management performance. By adjusting the refrigerant circulation pump's frequency, the system's cooling efficiency could be modulated. Specially designed for an 18,650-type lithium-ion battery module, the cooling system's thermal behaviour was meticulously tested and analysed under various conditions.Moving forward, hybrid cooling systems are poised to become ubiquitous in EV manufacturer BTMSs worldwide, promising enhanced efficiency and reliability.



III. Conclusion

Various cooling systems, including Air Cooling (AC), Liquid Cooling (LC), Refrigerant Direct Cooling (RDC), Cooling Systems using Phase Change Material (PCM), Thermoelectric Cooling (TC), Heat Pipe Cooling (HPC), and Hybrid Cooling (HC), have been synthesized and analysed for their application in electric vehicle (EV) batteries. Through comprehensive research, the advantages and disadvantages of each cooling system have been elucidated, offering valuable insights for the field of battery cooling in EVs.

- Air Cooling (AC) systems are lauded for their simplicity, affordability, and ease of implementation. However, they may struggle to meet the demands of high-temperature environments and large battery capacities.
- Liquid Cooling (LC) systems offer efficient heat dissipation and temperature control, but they require complex infrastructure and may be susceptible to leaks.
- Refrigerant Direct Cooling (RDC) systems exhibit promising potential for emergency cooling and thermal safety control, although they may incur higher costs and require intricate control strategies.
- Cooling Systems using Phase Change Material (PCM) leverage the latent heat absorption/release during phase transitions, offering efficient thermal management. However, they are limited by their narrow temperature range and reduced cooling efficacy beyond certain temperatures.
- Thermoelectric Cooling (TC) systems provide precise temperature control but suffer from high costs and low energy efficiency.
- Heat Pipe Cooling (HPC) systems offer excellent heat transfer capabilities and thermal performance. However, they may be limited by their heat load capacity.

- Hybrid Cooling (HC) systems combine multiple cooling technologies to capitalize on their respective advantages. While offering enhanced efficiency and flexibility, they may also be more complex and costly to implement.

By synthesizing and analysing these cooling systems, researchers gain valuable insights into their respective merits and limitations. This knowledge can inform the development of more effective and efficient battery cooling solutions for electric vehicles, ultimately contributing to advancements in EV technology.

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