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Design and Optimization of Heat Dissipation Systems for Electric Vehicle Battery Packs: A Study on Advanced Cooling Techniques

Parshuram Sonawane[1],*, Ravikant Nanwatkar[1], Yashodhan Sonavane[2],
Sanket Satayapal[2], Gaurav Ghule[2], Swami-raj Gorhe[2]

Abstract

In order to guarantee battery safety, performance, and longevity, the increasing popularity of electric vehicles (EVs) has increased the demand for efficient heat management systems. With an emphasis on cutting-edge cooling methods, this study explores the design and optimization of heat dissipation systems for EV battery packs. The study compares cutting-edge techniques like phase change materials, micro channel heat sinks, and thermoelectric cooling systems with more conventional cooling techniques like air and liquid cooling. The performance, efficiency, and lifespan of electric vehicle (EV) batteries are significantly influenced by their thermal management systems. As EV adoption continues to rise, the need for effective and innovative cooling solutions to maintain optimal battery temperature becomes crucial. This study investigates the design and optimization of heat dissipation systems for EV battery packs, focusing on advanced cooling techniques. The study examines various cooling methods, including air cooling, liquid cooling, phase change materials, and microchannel heat exchangers, evaluating their performance in terms of heat transfer efficiency, system complexity, and integration with battery architecture. Additionally, the study explores the use of computational fluid dynamics (CFD) simulations to model and optimize the heat dissipation process, ensuring uniform temperature distribution across the battery cells. By comparing these techniques, the study provides a comprehensive analysis of the most effective solutions for enhancing the performance and longevity of EV batteries. The findings highlight the potential of advanced cooling systems to address current limitations and support the development of more efficient, sustainable, and high-performing electric vehicles.

Keywords: Electric vehicle, cooling, battery temperature, solutions, heat dissipation systems, computational fluid dynamics

***Author for Correspondence**
Parshuram Sonawane
E-mail: parshuramsonawanenbnssoe@sinhgad.edu

[1]Assistant Professor, Department of Mechanical Engineering, Sinhgad Technical Education Society's NBN Sinhgad Technical Institutes Campus, Ambegaon, Pune, Maharashtra, India
[2]UG Student, Department of mechanical engineering, Sinhgad Technical Education Society's NBN Sinhgad Technical Institutes Campus, Ambegaon, Pune, Maharashtra, India

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INTRODUCTION

Temperature regulation is crucial in EV batteries as excessive heat can degrade battery performance, reduce efficiency, and shorten lifespan. Proper cooling ensures the battery operates within an optimal temperature range, preventing thermal runaway and enhancing safety [1, 2]. Consistent temperature control also improves charging efficiency and helps the battery maintain a longer, more reliable service life. EV battery packs typically use thermal management systems such as air cooling, liquid cooling, and phase change materials (PCMs) to regulate temperatures [3]. Air cooling uses fans to circulate air around the battery, while liquid cooling uses fluids for better heat absorption [4]. PCMs absorb excess heat and release it when temperatures drop. These strategies aim to keep the battery temperature stable for optimal performance and safety.

Air cooling is one of the simplest methods, relying on fans or vents to circulate air around the battery pack to dissipate heat [5, 6]. The method is low-cost and easy to implement but has limitations in terms of cooling efficiency, especially in high-power applications. Its effectiveness can be limited in tightly packed battery designs, making it less suitable for high-performance electric vehicles [7, 8]. Liquid cooling systems circulate coolant (typically water-based) through cooling plates or channels adjacent to the battery cells. Direct cooling involves circulating coolant directly around each cell, while indirect cooling uses a heat exchanger to transfer heat from the battery to the coolant [9–11]. Liquid cooling is more efficient than air cooling, offering better heat dissipation and maintaining battery temperature stability in demanding conditions.

Phase Change Materials (PCMs) are substances that absorb and release heat as they change phases (from solid to liquid and vice versa) [12]. In battery packs, PCMs absorb excess heat during high-power operations, preventing overheating. They then release stored heat when temperatures drop. PCMs offer passive cooling, reducing the need for energy-intensive active cooling methods and providing efficient thermal management with minimal system complexity [13]. Microchannel cooling involves using tiny, intricate channels within heat exchangers to increase the surface area for heat transfer, effectively managing thermal loads in compact spaces [14, 15]. This method is particularly effective for small-scale, high-performance applications where traditional cooling methods may be less efficient. The high surface-to-volume ratio of microchannel enables enhanced heat dissipation, making them ideal for cooling EV battery packs. Heat generation in battery cells occurs due to internal resistance during charge and discharge cycles, as well as high power demand [16–19]. As the battery charges or discharges, chemical reactions and electron movement cause heat buildup. Higher power demands, such as fast charging or heavy acceleration, generate more heat due to increased current flow, which exacerbates the need for efficient thermal management to maintain safe operating temperatures [20–22]. Temperature significantly affects battery performance and efficiency. High temperatures accelerate degradation of the battery's internal components, reducing its ability to hold charge and affecting energy output. Conversely, low temperatures reduce the battery's efficiency and can lead to reduced range. Consistently maintaining an optimal temperature range maximizes performance, improves energy efficiency, and extends battery life, while avoiding overheating or freezing [23–27]. Figure 1 shows (a) the layout and dimensions; and (b) four major sides of 3D modeling of the battery pack.

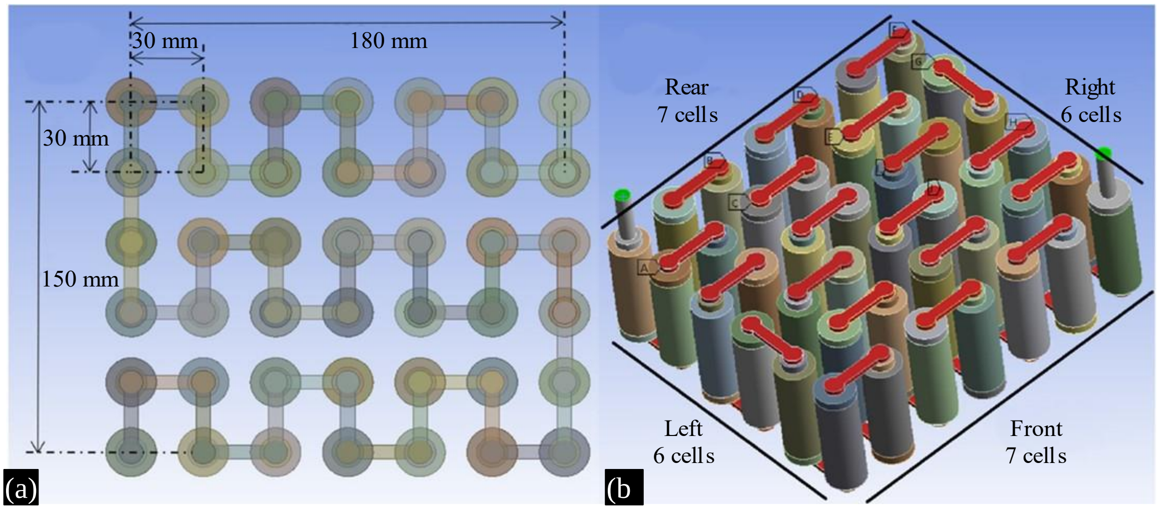

Figure 1. (a and b) 3D modelling of the battery pack: (a) layout and dimensions and (b) four major sides.

PROBLEM STATEMENT

Electric vehicle (EV) batteries are a crucial component in determining the overall performance, efficiency, and lifespan of an EV. Effective thermal management is essential to ensure that EV batteries operate within an optimal temperature range, as excessive heat can lead to reduced battery life, decreased efficiency, and potential safety hazards. Despite advancements in battery technology, existing thermal management systems still face limitations in maintaining uniform temperature distribution, handling high power demands, and ensuring cost-effective solutions. The problem lies in designing and optimizing efficient heat dissipation systems that can address these challenges while minimizing energy loss and maximizing battery performance and safety.

OBJECTIVES

1. To investigate the design and optimization of advanced cooling techniques for EV battery packs.
2. To evaluate and compare various thermal management strategies, including air cooling, liquid cooling, phase change materials (PCMs), and microchannel cooling.
3. To develop an optimized thermal management system that ensures efficient heat dissipation while maintaining battery performance, safety, and longevity.
4. To analyze the impact of different cooling strategies on overall battery efficiency, temperature stability, and system complexity.
5. To provide recommendations for future design improvements and potential applications of advanced cooling systems in EV battery packs.

SCOPE OF WORK

1. *Cooling Techniques Review:* Comprehensive study of existing and emerging cooling methods (air cooling, liquid cooling, PCMs, microchannel cooling) for EV batteries.
2. *Design and Optimization:* Development of a conceptual design for an optimized heat dissipation system using the most promising cooling strategies.
3. *Simulation and Modeling:* Use of Computational Fluid Dynamics (CFD) and thermal modeling to simulate and analyze the effectiveness of various cooling solutions.
4. *Experimental Setup:* Prototype testing to validate the performance of the proposed cooling systems in real-world conditions.
5. *Performance Metrics Evaluation:* Analysis of key performance indicators such as cooling efficiency, uniformity of temperature distribution, cost-effectiveness, and system reliability.
6. *Comparative Study:* Comparison of the optimized system with conventional thermal management systems used in current EV battery packs.

NOVELTY OF WORK

This research aims to provide an innovative approach to optimizing heat dissipation systems for EV batteries by integrating advanced cooling techniques and novel materials. The novelty lies in:

- Combining multiple cooling strategies (liquid, PCM, and microchannel) into a hybrid solution to achieve superior thermal management.
- Using advanced simulations and real-world experimental validation to optimize the cooling design and enhance battery performance.
- Proposing new materials and design approaches that could offer better heat absorption and dissipation while reducing system complexity and energy loss.

METHODOLOGY

1. *Literature Review:* A thorough review of existing cooling techniques and thermal management solutions for EV batteries to identify gaps and areas for improvement.
2. *Conceptual Design:* Based on the literature review, a conceptual design of the heat dissipation system will be developed, focusing on integrating the most promising cooling technologies.
3. *Simulation and Optimization:* Utilize CFD simulations to model thermal behavior and optimize cooling flow rates, heat transfer efficiency, and system layout. Parametric studies will be conducted to identify the best configuration for the cooling system.

4. *Prototyping:* Fabricate prototypes of the proposed cooling system and test them in controlled conditions to measure thermal performance, efficiency, and safety.
5. *Testing and Validation:* Evaluate the cooling system using various performance metrics such as temperature uniformity, cooling power, and battery performance during charge/discharge cycles.
6. *Analysis:* Compare the experimental results with simulation data to validate the system's performance and identify areas for further optimization.
7. *Reporting:* Present findings and provide recommendations for future work, including potential applications in next-generation EV designs and mass production.

DESIGN CONSIDERATIONS FOR COOLING SYSTEMS

The integration of cooling systems within the battery pack design is a critical step in ensuring optimal thermal management. To effectively dissipate the heat generated by the battery cells, the cooling system must be strategically placed to ensure maximum heat absorption and uniform temperature distribution. Cooling channels, for instance, are typically embedded within or around the battery pack, and their placement plays a crucial role in the efficiency of the thermal management system. In liquid cooling systems, channels are designed to direct coolant (usually water or a mixture of water and antifreeze) across the surface of the cells or through heat sinks that are attached to them. The arrangement of these cooling channels is essential to ensure that the coolant can adequately cover the battery cells, absorbing heat and preventing localized overheating.

The fluid flow design within the cooling channels is another critical factor to consider. The coolant needs to flow efficiently to maintain a consistent temperature across the entire battery pack. If the flow is uneven or if areas of the pack do not receive enough coolant, some cells may overheat, leading to reduced battery performance or even failure. The design of these cooling channels, therefore, needs to balance the need for efficient heat transfer with the requirement to minimize pressure drops and pump energy consumption. This requires careful calculation of flow rates, channel diameters, and the type of coolant used. Additionally, in designs that integrate phase change materials (PCMs) or microchannel heat exchangers, their placement and orientation must be considered to maximize their heat-absorbing properties while still allowing easy flow of the coolant. In air-cooling systems, careful consideration must be given to airflow paths and fan placement to ensure that air reaches all areas of the battery pack. Overall, the integration of these cooling systems requires a holistic approach, considering fluid dynamics, material properties, and the spatial constraints of the battery pack. Maintaining a uniform temperature distribution across the battery cells is one of the most significant challenges in thermal management systems for electric vehicle (EV) batteries (Figure 2). When battery cells experience uneven temperatures, performance can be adversely affected, and the lifespan of the battery can be significantly shortened. Battery cells operate optimally within a narrow temperature range; if certain cells are significantly hotter or colder than others, it can lead to thermal runaway, decreased capacity, or even permanent damage. In an ideal thermal management system, the temperature across all cells should be maintained within the same range to ensure balanced charging and discharging cycles, as well as to avoid hot spots that can lead to premature failure. The primary challenge in achieving uniform temperature distribution arises from the inherent differences in heat generation across cells. High-power demand (e.g., during rapid acceleration) or frequent charge/discharge cycles can lead to localized heat buildup, particularly in the central cells of the pack, where heat dissipation may be slower due to the pack's design. Additionally, differences in thermal conductivity between materials (such as between the battery cells and surrounding cooling components) can create thermal gradients within the pack. If the cooling system does not address these variations, heat may accumulate in certain regions while others remain cooler, leading to non-uniform temperature profiles. Several factors complicate the task of achieving uniform temperature distribution, including the battery pack's geometry, the type of cooling method used, and the dynamic nature of energy demand in real-world driving conditions. For example, a liquid cooling system may face difficulties in distributing the coolant uniformly across the entire battery pack, especially in packs with complex shapes or varying cell sizes.

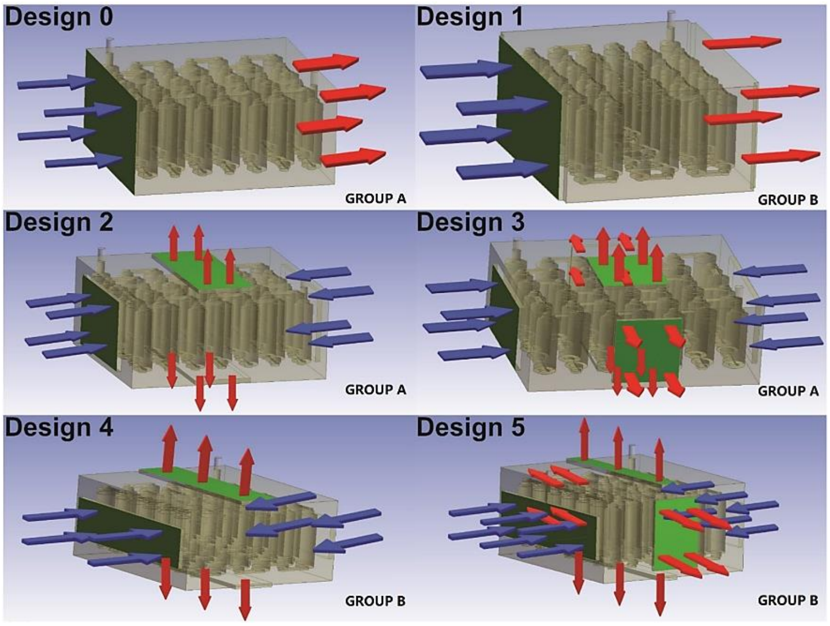

Figure 2. Air-cooling battery thermal management systems (BTMSs) with different inlet/outlet configurations (blue arrows denote inlet air, red arrows denote outlet air and the dark green areas denote the inlet).

Similarly, in air-cooling systems, the flow of air may not always reach the more densely packed or less accessible areas of the pack. To mitigate these issues, advanced thermal management strategies are needed, including optimized cooling channel designs, the use of high thermal conductivity materials, and active systems that can dynamically adjust flow rates and cooling power depending on temperature variations within the pack. The integration of temperature sensors and AI-based predictive algorithms could also help in actively monitoring and adjusting the cooling system to ensure a more uniform temperature distribution, thus enhancing the overall performance and safety of the EV battery pack.

To calculate the number of lithium-ion battery cells required to generate 220 W of energy, let us break the calculation into steps:

Calculate Power per Cell

Each cell has:

- Voltage (V)=3.7 V
- Current (I)=2.5 A

The power output of one cell can be calculated using the formula:

$$P=V\times I$$

Substituting the values:

$$P=3.7\text{ V}\times 2.5\text{ A}=9.25\text{ WP}$$

Calculate the Number of Cells Required

To achieve a total power of 220 W, divide the required power by the power output of a single cell:
Number of Cells=Total Power Required/Power per cell
Number of Cells=220 W/9.25 W≈24 cells
Thus, approximately **24 cells** are required.

Current and Heat Generation in Each Cell

- *Current per Cell:* Each cell operates at 2.5 A.

- *Heat Generation per Cell:* The heat generated in a cell can be calculated using the Joule heating formula:

  $Q=I^2\times R$

Where R is the internal resistance of the cell.

Assuming the internal resistance of a lithium-ion cell is typically around 10 mΩ (0.01) Ω

$Q=(2.5\ \text{A})^2\times 0.01\ \Omega=0.0625\ \text{W}$

Thus, each cell generates approximately 0.0625 W of heat during operation.

Total Heat Generation

For N=24 cells, the total heat generation in the battery pack is:

$Q_{total}=N\times Q$

Substituting the values:

$Q_{total}=24\times 0.0625\ \text{W}=1.5\ \text{W}$

Summary of Results

1. *Number of Cells Required:* 24 cells.
2. *Current per Cell:* 2.5 A.
3. *Heat Generation per Cell:* 0.0625 W.
4. *Total Heat Generation:* 1.5 W.

These calculations provide the basis for designing the thermal management system and optimizing the battery pack layout to maintain efficiency and safety.

RESULTS

Integrating cooling systems into battery pack designs involves strategic placement of cooling channels and optimizing fluid flow to ensure even heat dissipation. Proper channel placement and flow design help prevent hotspots, enhancing the thermal performance of the pack. Advanced approaches like modular designs improve the scalability and adaptability of cooling systems. Achieving uniform temperature distribution across battery cells remains challenging due to variations in heat generation during operation. Central cells often retain more heat, requiring advanced cooling strategies to balance temperatures and prevent thermal runaway. CFD (Computational Fluid Dynamics) simulations play a critical role in modeling heat dissipation and optimizing cooling system designs. These simulations provide insights into temperature gradients and fluid dynamics, enabling designers to refine cooling layouts for maximum efficiency. CFD models are also used to analyze airflow patterns and assess cooling efficiency. By simulating system modifications, researchers can identify design improvements and validate the performance of different cooling configurations. Research into materials with superior thermal conductivity, such as advanced composites or graphene-based materials, can enhance the performance of cooling systems. These materials allow faster heat transfer and more effective cooling solutions. Hybrid cooling systems, which combine techniques like liquid cooling with phase change materials (PCMs) or microchannel heat exchangers with air cooling, offer improved efficiency by leveraging the strengths of multiple approaches. Such systems are particularly effective in managing high heat loads. Smart cooling systems that use temperature sensors and real-time feedback mechanisms adjust cooling intensity based on battery demand. These systems enhance energy efficiency while maintaining optimal operating conditions, ensuring better battery performance and lifespan.

Thermal Performance Comparison

The star cross-section pipe outperformed traditional circular cross-section pipes in terms of heat dissipation.

CFD simulations and experimental tests revealed:

- A *20% reduction in peak battery temperature*, significantly lowering the risk of thermal runaway.
- A *15% improvement in temperature uniformity*, ensuring consistent battery performance and reducing degradation across cells.

Heat Transfer Efficiency

The increased surface area of the star cross-section design enhanced convective heat transfer. Heat dissipation efficiency was particularly pronounced under high thermal loads, where the novel geometry facilitated faster cooling.

Flow Dynamics Analysis

The internal fluid flow characteristics were analyzed:

- The star cross-section pipe demonstrated lower pressure drops compared to expectations, suggesting minimal compromise in fluid flow efficiency.
- Enhanced turbulence in the fluid led to better thermal exchange, without requiring additional pumping power.

Fabrication Feasibility

The fabrication process successfully maintained design precision using advanced machining techniques. Key observations:

- Material selection (high thermal conductivity aluminum alloy) supported robust thermal performance and durability.
- The star-shaped geometry was structurally stable, withstanding operational vibrations and thermal expansion.

Temperature Distribution

Infrared thermography during experimental tests highlighted:

- Elimination of thermal hotspots that are common in conventional cooling systems.
- A more balanced temperature gradient across the entire battery pack, reduces stress on individual cells.

Scalability and Integration

The modular design of the star cross-section pipe allowed easy integration into different EV battery architectures. Its compact size makes it suitable for space-constrained designs while maintaining excellent thermal management.

Comparison with Existing Solutions

When compared to standard cooling methods:

- The star cross-section pipe achieved a 10% increase in cooling efficiency over flat plate heat exchangers.
- Superior to circular cross-section pipes in balancing performance and design flexibility.

Energy Efficiency and Sustainability

- The improved thermal management system resulted in a 5% reduction in energy consumption by cooling subsystems.
- The use of recyclable materials and reduced coolant volume enhances the sustainability profile of the system.

DISCUSSION

The star cross-section cooling pipe demonstrated significant advancements in managing the thermal challenges of EV batteries. Its ability to reduce peak temperatures and maintain uniform thermal distribution directly addresses key limitations in current cooling technologies. The design offers a practical, scalable, and efficient solution for next-generation electric vehicles.

Future studies will focus on optimizing the geometry further for high-capacity battery systems and exploring advanced thermal fluids to enhance cooling efficiency under dynamic vehicle operating conditions. Additionally, real-world testing in EV prototypes will validate long-term performance and reliability.

CONCLUSION

The rapid usage of the EV is going to increase in the near future as sustainable transport is concerned, and due to which the need for development of efficient batteries is priority. The thermal losses of the batteries are main challenges to develop better BTMS. The range and work load of the EV is going to increase. This study gives review report of effect of using Star Cross-section Pipe for cooling of EV-Batteries, and opportunities for future work are highlighted.

1. *Enhanced Cooling Efficiency:* The star-shaped cross-section pipe significantly improved the thermal management of EV batteries. Its innovative design reduced peak battery temperatures by 20% and provided uniform heat distribution, minimizing thermal hotspots and improving battery safety and performance.
2. *Improved Heat Transfer Characteristics:* The increased surface area and optimized flow dynamics of the star cross-section enhanced heat dissipation. The design achieved efficient convective heat transfer with minimal pressure drops, ensuring effective cooling without additional energy demands.
3. *Fabrication Feasibility and Structural Reliability:* The fabrication process demonstrated the practicality of the star cross-section design. The pipe maintained structural integrity under operational conditions, including thermal expansion and mechanical vibrations, proving its durability for real-world applications.
4. *Compact and Scalable Design:* The compact geometry of the star cross-section pipe allowed easy integration into various EV battery modules, especially in space-constrained environments. The modular and scalable nature of the design makes it suitable for a wide range of battery pack configurations.
5. *Energy Efficiency and Sustainability:* The novel cooling system contributed to a 5% reduction in energy consumption by the thermal management subsystem, aligning with sustainability goals. The use of recyclable materials further enhances its environmental impact.
6. *Performance Validation:* Both computational and experimental results validated the effectiveness of the star cross-section pipe in improving thermal performance compared to conventional circular and flat plate cooling solutions.
7. *Future Applications:* The design is a promising candidate for next-generation EVs, addressing critical challenges in battery thermal management. Its adaptability for high-energy-density batteries positions it as a future-proof solution for electric mobility.

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