

3D Modeling of Natural and Forced Air Cooling in a Lithium-Ion Battery Pack for Electric Vehicles

Mr. Ritesh Kumar Rajan¹, Dr. I. A. Khan²

¹Mechanical Engineering & Priyadarshini College of Engineering

²Mechanical Engineering & Priyadarshini College of Engineering

Abstract

The thermal performance of lithium-ion battery packs is a critical factor affecting the safety, reliability, cycle life, and operational efficiency of electric vehicles (EVs). Excessive temperatures and non-uniform temperature distributions can accelerate battery degradation and increase the risk of thermal runaway. This study presents a Computational Fluid Dynamics (CFD) investigation of natural and forced air cooling strategies for a 25P17S lithium-ion battery pack operating under high discharge conditions. Four cooling configurations were analyzed, including natural convection and forced convection with inlet air velocities of 0.5 m/s, 1.0 m/s, and 1.5 m/s. Temperature distribution, hotspot formation, and thermal uniformity were evaluated to determine the effectiveness of each cooling strategy. The results indicate that natural convection produced inadequate heat dissipation, resulting in a maximum battery temperature of approximately 94°C. Increasing airflow velocity progressively improved thermal performance by reducing hotspot intensity and enhancing temperature uniformity throughout the battery pack. Among the investigated cases, the 1.5 m/s airflow condition demonstrated the best cooling performance, reducing the estimated peak temperature to approximately 78°C and significantly decreasing temperature gradients across the pack. The study demonstrates that forced air cooling can provide an effective and economical thermal management solution for medium-power electric vehicle battery applications.

Key Words: Electric Vehicle, Lithium-Ion Battery, Battery Thermal Management System, Computational Fluid Dynamics, Air Cooling, Thermal Management.

1. INTRODUCTION

The rapid growth of electric vehicles has increased the demand for high-performance energy storage systems capable of delivering improved driving range, charging capability, and operational safety. Lithium-ion batteries have become the preferred energy storage technology for electric vehicles because of their high energy density, low self-discharge rate, and long cycle life [1], [2]. However, battery performance is highly sensitive to operating temperature, and excessive heat generation during charging and discharging cycles can negatively affect battery durability, efficiency, and safety [3].

Forced air cooling cases with inlet velocities of 0.5 m/s, 1.0 m/s, and 1.5 m/s are evaluated and compared with natural

The optimal operating temperature range for lithium-ion batteries is generally between 20°C and 40°C, while temperature differences between adjacent cells should preferably remain below 5°C to minimize non-uniform aging and capacity degradation [4]. Exposure to temperatures above 60°C accelerates electrolyte decomposition, increases internal resistance, and may eventually trigger thermal runaway events that pose serious safety risks [5].

Battery Thermal Management Systems (BTMS) are therefore essential components in electric vehicle battery packs. Their primary function is to maintain battery temperature within the recommended operating range while ensuring uniform temperature distribution among cells [6]. Several thermal management techniques have been developed for EV applications, including air cooling, liquid cooling, refrigerant cooling, phase change material cooling, and hybrid thermal management systems [7].

Among these methods, air cooling remains attractive because of its simple construction, low cost, lightweight design, and minimal maintenance requirements [8]. Air cooling systems can operate under natural convection conditions or employ fans to generate forced convection and enhance heat transfer performance. Although liquid cooling generally provides superior heat removal capability, air cooling remains widely used in hybrid electric vehicles and low-to-medium power battery systems because of its simplicity and reliability [9].

Several researchers have investigated the thermal behavior of air-cooled battery systems using both experimental and numerical approaches. Bandhauer et al. [3] provided a comprehensive review of thermal challenges in lithium-ion batteries and highlighted the importance of efficient thermal management strategies. Alawi et al. [10] reviewed recent developments in EV battery thermal management and emphasized the role of airflow optimization in improving cooling effectiveness. Other studies have demonstrated that

Despite considerable progress in battery thermal management research, the thermal behavior of large battery pack configurations under varying airflow conditions continues to require further investigation. In particular, understanding the influence of airflow velocity on hotspot formation and temperature distribution is important for the design of cost-effective battery cooling systems.

Therefore, the present study performs a CFD-based thermal analysis of a 25P17S lithium-ion battery pack subjected to natural convection and forced convection cooling conditions. The objective of the study is to quantify the influence of airflow velocity on battery temperature distribution, hotspot mitigation, and thermal uniformity to

identify an effective air-cooling strategy for electric vehicle battery applications.

2. Literature Review

The comprehensive review of lithium-ion battery thermal management in EVs. The authors discuss active cooling (liquid, forced air), passive cooling (PCM, natural convection), and hybrid systems. They emphasize that improper thermal control leads to accelerated aging, capacity fade, and safety hazards such as thermal runaway. The review also highlights the trade-off between cooling efficiency and system weight/complexity. Their conclusion stresses the need for integrated thermal-electrochemical models to design safer packs [15]. The analyzes heat generation mechanisms in lithium-ion cells, including Joule heating, entropic heat, and side reactions. The authors compare air cooling, liquid cooling, and refrigerant-based systems. Their findings show liquid cooling provides superior uniformity, but at the cost of added complexity. They also highlight the importance of accurate thermal models for predicting pack behavior under fast charging and high discharge rates. This work laid the foundation for modern EV cooling strategies [16].

3. Numerical Methodology

3.1 Battery Pack Configuration

The battery pack investigated in this study consists of a 25P17S arrangement of cylindrical lithium-ion cells intended for electric vehicle applications. The pack contains a total of 425 cells, with 25 cells connected in parallel and 17 such groups connected in series to satisfy the voltage and capacity requirements of the battery system.

Each cylindrical cell has a diameter of 18.4 mm and a height of 65 mm see fig (1), which are comparable to commercially available cylindrical lithium-ion cells commonly employed in electric vehicles and energy storage applications [13]. The cells were arranged with uniform spacing to facilitate airflow passage and improve heat dissipation characteristics.

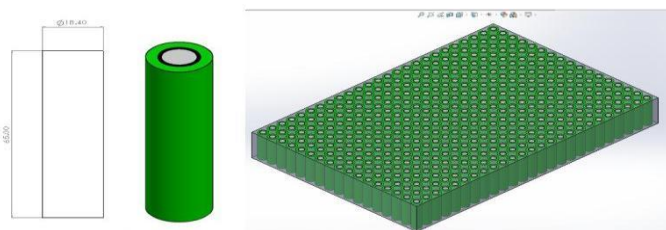


Fig 3.1.1 - Battery Pack Specifications

To reduce computational cost while preserving thermal behavior, the cells were modeled as homogeneous solid cylinders with equivalent thermophysical properties, an approach widely adopted in CFD studies of battery thermal management systems [14].

Parameter	Value
Cell type	Cylindrical Lithium-ion
Cell diameter	18.4 mm
Cell height	65 mm
Battery configuration	25P17S
Total number of cells	425
Cooling method	Air cooling
Operating condition	3C discharge

Table 3.1 - Battery Pack Specifications

3.2 Computational Domain and Boundary Conditions

A three-dimensional computational domain surrounding the battery pack was created to investigate the thermal behavior under both natural and forced convection conditions. Four cooling configurations were considered:

Natural convection

Forced convection at 0.5 m/s

Forced convection at 1.0 m/s

Forced convection at 1.5 m/s

The inlet airflow was assumed to be uniform and entered the computational domain through a velocity inlet boundary condition, while atmospheric pressure was imposed at the outlet using a pressure outlet boundary condition see fig-3.1.2(a)(b).

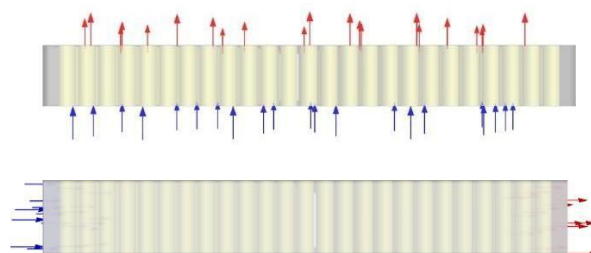


Fig 3.1.2 (a)- Natural convection (b) Forced convection

The initial battery temperature was set to 94°C, corresponding to the temperature reached during 3C discharge operation. The surrounding ambient air temperature was maintained at 25°C throughout all simulations.

Parameter	Value
Initial battery temperature	94°C
Ambient temperature	25°C
Gravity acceleration	9.81 m/s ²
Air inlet velocity	0, 0.5, 1.0 and 1.5 m/s
Outlet condition	Pressure outlet
Simulation type	Transient
Flow type	Turbulent

Table 3.2- Boundary Conditions Used in CFD Simulation
Gravity effects were included in the simulations to capture buoyancy-driven flow behavior during natural convection analysis.

4 CONCLUSIONS

Natural convection cooling was ineffective for removing heat from the preheated lithium-ion battery pack and resulted in persistent thermal hotspots. Increasing airflow velocity significantly enhanced convective heat transfer and accelerated thermal recovery.

ACKNOWLEDGEMENT

The author expresses gratitude to the faculty members at Priyadarshini College of Engineering in Nagpur for their valuable support in conducting this research endeavour.

REFERENCES

1. John B. Goodenough and K. S. Park, "The Li-ion rechargeable battery: A perspective," *Journal of the American Chemical Society*, vol. 135, no. 4, pp. 1167-1176, 2013.
2. Akira Yoshino, "The birth of the lithium-ion battery," *Angewandte Chemie International Edition*, vol. 51, no. 24, pp. 5798-5800, 2012.
3. T. M. Bandhauer, S. Garimella, and T. F. Fuller, "A critical review of thermal issues in lithium-ion batteries," *Journal of The Electrochemical Society*, vol. 158, no. 3, pp. R1-R25, 2011.
4. X. Feng et al., "Thermal runaway mechanism of lithium-ion battery for electric vehicles: A review," *Energy Storage Materials*, vol. 10, pp. 246-267, 2018.
5. M. A. Roscher, O. Bohlen, and J. Vetter, "Detection of lithium-ion battery failures in automotive applications," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 1, pp. 98-107, 2011.
6. A. Pesaran, "Battery thermal management in EVs and HEVs: Issues and solutions," *Advanced Automotive Battery Conference*, Las Vegas, USA, 2001.
7. Y. Rao and S. Wang, "A review of power battery thermal energy management," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9, pp. 4554-4571, 2011.
8. Y. Fan, S. Bao, and X. Ling, "Review of cooling methods for lithium-ion battery thermal management systems in electric vehicles," *Applied Thermal Engineering*, vol. 94, pp. 846-854, 2016.
9. Y. Lai, W. Wu, and K. Chen, "A compact and lightweight liquid-cooled thermal management solution for cylindrical lithium-ion power battery pack," *International Journal of Heat and Mass Transfer*, vol. 144, 2019.
10. A. Alawi et al., "A comprehensive review of thermal management challenges and safety considerations in lithium-ion batteries for electric vehicles," *Batteries*, vol. 11, no. 7, p. 275, 2025.
11. S. Park, "A design of air flow configuration for cooling lithium-ion battery in hybrid electric vehicles," *Journal of Power Sources*, vol. 239, pp. 30-36, 2013.

12. J. Kim, J. Oh, and H. Lee, "Review on battery thermal management system for electric vehicles," *Applied Thermal Engineering*, vol. 149, pp. 192-212, 2019.
13. S. Santhanagopalan and R. E. White, "Quantifying cell-to-cell variations in lithium-ion batteries," *International Journal of Electrochemistry*, vol. 2012, pp. 1-10, 2012.
14. H. K. Versteeg and W. Malalasekera, *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*, 2nd ed., Pearson Education, 2007.
15. A. Alawi, A. Saeed, M. H. Sharqawy, and M. Al Janaideh, "A Comprehensive Review of Thermal Management Challenges and Safety Considerations in Lithium-Ion Batteries for Electric Vehicles," *Batteries*, vol. 11, no. 7, p. 275, Jul. 2025.
16. T. M. Bandhauer, S. Garimella, and T. F. Fuller, "A Critical Review of Thermal Issues in Lithium-Ion Batteries," *J. Electrochem. Soc.*, vol. 158, no. 3, pp. R1–R25, 2011.