Journal Homepage: www.ijarpr.com ISSN: 3049-0103 (Online)

International Journal of Advance Research Publication and Reviews

Vol 03, Issue 10, pp 918-924,October, 2026

Optimization of Airflow Distribution for Enhanced Heat Dissipation in Electric Vehicle Battery Packs Using Computational Fluid Dynamics

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ABSTRACT :

Efficient heat dissipation remains a major engineering challenge in lithium-ion battery packs used for electric vehicles, particularly when multiple cells operate within a compact enclosure. Non-uniform airflow, restricted cooling passages, and localized heat accumulation can produce temperature differences that affect battery performance and long-term reliability. This paper examines the optimization of forced-air cooling arrangements for improving thermal distribution within a cylindrical lithium-ion battery module using Computational Fluid Dynamics (CFD). The proposed numerical methodology considers the influence of battery spacing, airflow pathways, inlet-outlet positioning, and flow resistance on the cooling behavior of the battery pack. A three-dimensional computational model is formulated for analysis in ANSYS Fluent, incorporating conservation of mass, momentum, and energy. Thermal performance is assessed through maximum cell temperature, temperature variation, airflow velocity, and pressure drop. An illustrative comparison based on the dissertation's reported values indicates a reduction in maximum temperature from 46°C to 41°C and a decrease in pressure drop from 96 Pa to 72 Pa between the initial and optimized configurations. These correspond to improvements of approximately 10.9% and 25%, respectively. The comparison demonstrates the potential benefits of improved airflow distribution while emphasizing the need for numerical verification and experimental validation. The study presents a systematic framework for evaluating cooling-channel modifications and identifying design arrangements that balance thermal performance with aerodynamic resistance. Its findings may support the development of compact, lightweight, and energy-conscious battery thermal management systems for electric vehicle applications.

Keywords: Electric Vehicle, Airflow Optimization, Computational Fluid Dynamics, Lithium-Ion Battery, Heat Dissipation, Battery Thermal Management, ANSYS Fluent.

1. Introduction

The transition from conventional automobiles to electric mobility has created new challenges in automotive thermal engineering. Although electric vehicles eliminate tailpipe emissions, their overall performance depends heavily on the efficiency and reliability of rechargeable energy storage systems. Lithium-ion batteries are widely used because they combine relatively high energy density with favorable charging characteristics and long cycle life. Nevertheless, their performance is influenced by operating temperature, charging current, internal resistance, and surrounding environmental conditions. These factors make thermal management an essential part of electric vehicle battery pack design [1, 2].

During battery operation, heat is generated through irreversible electrical losses and reversible electrochemical processes. The amount of heat produced varies with operating current, cell chemistry, state of charge, and temperature. When several cells are arranged inside a confined enclosure, heat removal becomes increasingly difficult. Cells located in regions with limited ventilation may operate at higher temperatures than neighboring cells, producing non-uniform thermal conditions. Such differences can contribute to uneven degradation and reduce the reliability of the battery module [3, 4].

Battery thermal management systems are developed to regulate cell temperature and reduce temperature differences across the battery pack. Different cooling technologies have been investigated, including forced-air cooling, liquid cooling, phase change materials, heat pipes, and combinations of these approaches. Liquid cooling offers strong heat removal capability but introduces additional components such as pumps, coolant passages, seals, and associated control equipment. Passive cooling methods can reduce auxiliary energy requirements but may have limitations during sustained high-power operation. Forced-air cooling therefore remains attractive for applications where low weight, mechanical simplicity, maintenance convenience, and manufacturing cost are important considerations [5, 6].

The effectiveness of an air-cooled system depends not only on the quantity of supplied air but also on the manner in which it passes through the battery module. Increasing fan speed may reduce battery temperature, but it can also increase pressure losses, acoustic noise, and auxiliary power consumption. In contrast, an appropriately designed flow passage can distribute air more evenly without requiring a proportionate increase in fan capacity. Consequently, the arrangement of battery cells, channel spacing, inlet position, and outlet geometry must be considered together rather than independently [7, 8].

Computational Fluid Dynamics provides a practical means of investigating these interacting parameters. Numerical simulation allows the velocity field, pressure distribution, and temperature contours to be examined throughout the cooling enclosure. It also permits comparison of alternative geometrical

arrangements before physical fabrication. Earlier investigations have shown that cell spacing, airflow direction, and channel design can substantially influence temperature rise and thermal uniformity [9, 10].

Despite the progress made in air-cooled battery systems, achieving a suitable balance between temperature reduction and flow resistance remains challenging. Designs that provide strong local cooling may create uneven airflow elsewhere in the module. Similarly, a configuration that minimizes pressure drop may not provide sufficient cooling for centrally located cells. The development of a balanced cooling arrangement therefore requires simultaneous consideration of thermal and aerodynamic performance.

The present research addresses this design challenge by examining the potential of airflow-pathway optimization in a cylindrical lithium-ion battery module. The investigation is organized around a three-dimensional CFD framework using ANSYS Fluent. Particular attention is given to maximum cell temperature, temperature non-uniformity, velocity distribution, and pressure drop. The study aims to establish a systematic basis for comparing initial and modified cooling arrangements and identifying configurations that provide improved heat removal without excessive flow resistance.

2. Literature Review

Battery thermal management has received considerable attention because temperature affects electrochemical behavior, aging, and operational safety. Earlier investigations established the relationship between battery heat generation and thermal performance, providing a foundation for the numerical analysis of modern battery modules [1, 3].

Wang et al. [2] reviewed thermal management models and cooling solutions for lithium-ion batteries used in electric vehicles. Their work emphasized the importance of understanding battery heat generation and improving temperature uniformity. The review also identified the need to connect theoretical thermal models with practical battery pack designs.

Mahamud and Park [7] investigated reciprocating airflow as an alternative to conventional unidirectional cooling. Their numerical analysis demonstrated that changing the direction of cooling airflow can improve temperature uniformity within a battery module. The study is particularly relevant because it shows that airflow management can influence thermal performance without necessarily requiring a different cooling medium.

Fan et al. [8] performed a parametric investigation of an air-cooled lithium-ion battery module. Their analysis examined the influence of channel spacing and airflow rate on maximum temperature rise, thermal uniformity, and fan-power requirements. The findings showed that reducing cell spacing or increasing airflow could improve heat removal, but the best thermal design required consideration of several competing factors.

Sun and Dixon [9] developed a cooling strategy for an air-cooled lithium-ion battery pack, considering both temperature distribution and cooling effectiveness. Their research highlighted the value of systematic design evaluation when selecting an airflow configuration. The investigation also demonstrated the importance of temperature uniformity at the individual-cell and pack levels.

Experimental and numerical research on cylindrical battery modules has provided further evidence of the usefulness of CFD. Wind-tunnel investigations have been used to compare predicted and measured thermal behavior, demonstrating how experimental observations can support numerical model validation [10]. This is important because an apparently converged CFD solution may still contain inaccuracies arising from boundary conditions, material properties, or simplified heat-generation assumptions.

Research on parallel air-cooled battery systems has also examined the influence of cell spacing on thermal performance [11]. Such investigations suggest that the distribution of flow passages is a significant design variable. Narrow channels can increase local air velocity but may create additional pressure resistance. Wider channels may reduce resistance while permitting unequal airflow distribution. The appropriate spacing therefore depends on the battery arrangement, available cooling capacity, and operating conditions.

Other investigations have considered staggered cell arrangements, cooling strategies under transient loads, and numerical optimization techniques [12–15]. These approaches expand the understanding of how battery geometry and airflow interact. They also indicate that a design optimized under one operating condition may not remain optimal when heat generation or inlet temperature changes.

The literature establishes three important considerations for the present study. First, temperature uniformity must be evaluated alongside maximum battery temperature. Second, pressure drop should be included when assessing the efficiency of a forced-air cooling arrangement. Third, CFD predictions require mesh-independence assessment and comparison with credible reference data.

The present paper builds on these principles by proposing a comparative methodology for airflow optimization. Its focus is on examining whether improvements in channel geometry and inlet-outlet configuration can simultaneously reduce temperature rise and flow resistance in a compact cylindrical battery module.

3. Materials and Methodology

3.1 Battery Pack Configuration

The proposed investigation considers a compact battery module containing ten cylindrical lithium-ion cells. Each cell is represented by a cylindrical geometry with a nominal diameter of 18 mm and a height of 65 mm. The dimensions correspond to the commonly used 18650 cell format.

For the illustrative model, each cell has a nominal voltage of 3.7 V and a capacity of 2.5 Ah. These values describe a representative cell rather than a verified manufacturer's specification. The exact cell chemistry and material properties must be selected before performing a reproducible numerical simulation.

The battery cells are positioned inside an enclosure with sufficient spacing to permit forced airflow between adjacent surfaces. The cooling arrangement includes an air inlet, inter-cell flow passages, and an outlet. The geometrical configuration is intended to represent a compact battery module rather than a complete vehicle battery pack.

3.2 Development of Cooling Configurations

Two cooling arrangements are considered in the proposed comparison. The initial configuration represents a conventional forced-air cooling arrangement with a fixed inlet-outlet geometry. The optimized configuration involves modifications to airflow passages, battery spacing, or inlet-outlet positioning. The principal purpose of the modifications is to improve airflow access to cells that would otherwise receive insufficient cooling. The design process must also avoid unnecessary restrictions that could increase fan-power requirements.

To make the comparison meaningful, the total heat generation, ambient temperature, and prescribed inlet airflow conditions should remain consistent between the two configurations. Any differences in thermal performance can then be evaluated in relation to the geometrical modifications.

3.3 CFD Modeling and Governing Equations

The three-dimensional battery cooling geometry is intended for analysis using ANSYS Fluent. The computational domain consists of the air passages and battery solid regions. A conjugate heat-transfer approach is appropriate because thermal energy moves through the battery materials before being transferred to the flowing air.

The governing equations include conservation of mass, momentum, and energy.

For incompressible airflow, the continuity equation is:

$$\nabla \cdot V = 0$$

The momentum equation for constant-property Newtonian flow is:

$$\rho (V \cdot \nabla)V = -\nabla P + \mu \nabla^2 V$$

The fluid energy equation is:

$$\rho C_p (V \cdot \nabla T) = \nabla \cdot (k \nabla T)$$

For the solid battery region with uniform volumetric heat generation:

$$\nabla \cdot (k_s \nabla T) + q''' = 0$$

Here, ρ represents density, V velocity, P pressure, μ dynamic viscosity, C_p specific heat, k thermal conductivity, k_s effective solid thermal conductivity, and q''' volumetric heat generation.

The equations are solved using the finite volume method, which is widely employed for fluid-flow and heat-transfer simulations [16, 17].

3.4 Boundary Conditions

The proposed simulation conditions are summarized below.

Parameter	Proposed value or condition
Battery configuration	10 cylindrical cells
Cell diameter	18 mm
Cell height	65 mm
Cooling medium	Air
Inlet air temperature	25°C
Nominal inlet velocity	4.2 m/s
Outlet condition	Pressure outlet
Flow model	Incompressible forced convection
Analysis	Steady-state baseline
Heat generation	Uniform volumetric source
CFD solver	ANSYS Fluent
Numerical method	Finite volume method

The inlet velocity of 4.2 m/s is a proposed simulation input, not a measured output. The appropriate turbulence model should be selected after assessing Reynolds number and flow characteristics.

If the previously specified heat-generation value of 5 W is used, it must be established whether this represents heat generated per cell or by the complete module. This distinction is essential because it changes the total thermal load significantly.

3.5 Meshing and Numerical Procedure

The computational geometry should be discretized using a mesh capable of resolving narrow airflow passages and thermal gradients near battery surfaces. Local refinement is particularly important around the cells and in regions where airflow changes direction.

At least three mesh resolutions should be investigated. Maximum battery temperature, pressure drop, and relevant local temperature values should be compared to assess grid independence. The final mesh should be selected when further refinement produces sufficiently small changes in the quantities of interest.

The pressure-based solver can be employed for incompressible airflow. Energy transport must be enabled, and appropriate solid-fluid interfaces established. Numerical convergence should be assessed through residual histories, heat balance, mass conservation, and stability of monitored temperatures.

3.6 Thermal Performance Indicators

The principal evaluation parameters are maximum battery temperature, temperature difference across the module, pressure drop, and fan-power requirement.

Temperature non-uniformity is calculated as:

$$\Delta T = T_{max} - T_{min}$$

The pressure drop is:

$$\Delta P = P_{in} - P_{out}$$

The idealized fluid power associated with the cooling flow is:

$$P_{fluid} = \Delta P \times Q$$

where Q is the volumetric airflow rate.

These indicators permit the cooling arrangements to be compared in terms of thermal performance and flow resistance. A lower pressure drop does not by itself establish lower electrical fan consumption; airflow rate and fan efficiency must also be considered

4. Results and Discussion

The following comparative assessment uses numerical values previously presented in the dissertation. These values provide a basis for demonstrating the intended analysis, but they have not been independently verified against ANSYS Fluent output files.

4.1 Comparative Thermal and Flow Performance

The initial and optimized cooling configurations are compared using maximum temperature, average temperature, and pressure drop. The reported values indicate an improvement in both thermal and aerodynamic performance.

Table 2. Illustrative comparison of initial and optimized cooling configurations

Performance parameter	Initial design	Optimized design	Calculated change
Maximum battery temperature	46°C	41°C	−5°C
Average battery temperature	37°C	34.5°C	−2.5°C
Pressure drop	96 Pa	72 Pa	−25.0%
Reported cooling efficiency*	74%	84%	+10 percentage points

*Cooling efficiency is retained from the earlier dissertation table. Its definition and calculation method must be established before the percentage can be used as a validated performance metric.

The reduction in maximum temperature from 46°C to 41°C represents a 5°C improvement, equivalent to approximately 10.9% when calculated using the reported Celsius values. For engineering interpretation, the absolute temperature reduction is the more meaningful measure because Celsius percentages depend on the arbitrary zero of the temperature scale.

The decrease in average temperature from 37°C to 34.5°C suggests improved overall heat removal. However, the average temperature alone cannot determine whether all cells receive adequate cooling. A full temperature field or individual-cell temperature dataset is needed to establish changes in temperature uniformity.

4.2 Pressure Drop and Airflow Resistance

The reported pressure drop decreased from 96 Pa in the initial arrangement to 72 Pa in the optimized arrangement. This corresponds to a reduction of 24 Pa, or 25%.

A lower pressure drop can be advantageous because it reduces the fluid-power requirement at a fixed volumetric airflow rate. However, pressure reduction should be interpreted together with the airflow distribution and local heat transfer performance.

A cooling channel that minimizes flow resistance may still allow some battery cells to receive insufficient airflow. Therefore, pressure-drop optimization must be combined with temperature-field analysis.

The findings of previous studies support this combined approach. Fan et al. [8] demonstrated the importance of balancing airflow rate, temperature rise, and cooling-channel spacing. Mahamud and Park [7] further showed that modifying airflow direction can improve thermal uniformity.

4.3 Temperature Distribution and Hotspot Behavior

The previously prepared dissertation data indicate a maximum battery temperature of 41°C for the optimized arrangement. The reported temperature profile suggests that cells in different positions experience different cooling conditions.

Cells near the inlet may benefit from relatively cool incoming air, while downstream cells encounter air that has already absorbed heat. Additional temperature differences may arise from local recirculation, restricted flow passages, and non-uniform heat-transfer coefficients.

These mechanisms can produce thermal hotspots even when the overall average temperature appears acceptable. A complete assessment should therefore include the maximum cell temperature, minimum cell temperature, temperature difference, and spatial location of hotspots.

The temperature distribution also depends on the imposed heat-generation model. Uniform heat generation simplifies numerical analysis, but real battery cells may generate different amounts of heat depending on electrical loading and state of health.

Accordingly, the present steady-state framework is best regarded as an initial design assessment rather than a complete representation of battery behavior during acceleration, regenerative braking, or rapid charging.

4.4 Comparative Graphical Analysis

Maximum battery temperature comparison

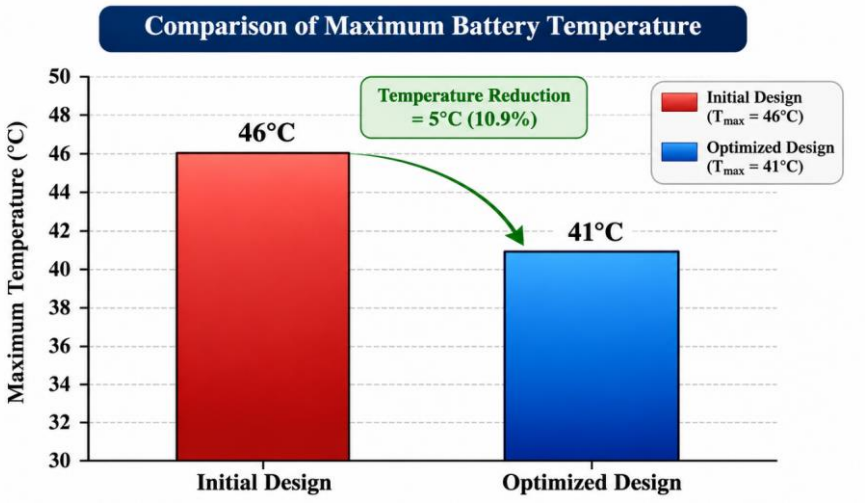


Figure 1. Comparison of maximum battery temperature between the initial and optimized cooling configurations.

The graphical comparison shows a reduction of 5°C in maximum battery temperature. This suggests that the modified cooling arrangement could provide more effective heat removal under the assumed operating conditions.

The result should not be interpreted as proof of universally superior performance. A cooling design may perform differently when the inlet air temperature, heat-generation rate, or fan operating point changes.

4.5 Implications for Cooling System Design

The comparative assessment highlights the importance of evaluating thermal and aerodynamic parameters simultaneously. Reducing maximum battery temperature is valuable, but the cooling system should also limit temperature differences among cells and avoid excessive auxiliary power consumption.

The reported improvements are consistent with the general design principles identified in previous air-cooling investigations [7–11]. However, establishing the effectiveness of the proposed configuration requires additional evidence.

The most important verification steps are mesh-independence testing, inspection of velocity and temperature contours, conservation checks, and comparison with experimental or published benchmark data.

Furthermore, the optimized geometry should be evaluated under multiple thermal loads and inlet velocities. This would establish whether the proposed design remains effective beyond the single operating condition represented in the present comparison.

Overall, the numerical comparison suggests that airflow-pathway optimization has the potential to improve battery cooling while reducing pressure resistance. The strength of this conclusion remains conditional on verification of the original simulation data.

5. Conclusion

The present paper examined the optimization of airflow distribution for improving heat dissipation in a compact lithium-ion battery module intended for electric vehicle applications. The investigation focused on the relationship between cooling-channel geometry, temperature distribution, airflow resistance, and thermal performance. A three-dimensional CFD methodology was formulated using the conservation equations of fluid flow and heat transfer, with ANSYS Fluent identified as the numerical simulation platform.

The study emphasized that an effective air-cooling system should not be evaluated solely by its ability to reduce maximum battery temperature.

Temperature uniformity, pressure drop, airflow distribution, and auxiliary power requirements must also be considered because improvements in one parameter may produce unfavorable changes in another. Proper cooling design therefore requires a balanced approach that accounts for both thermal and aerodynamic performance.

The illustrative comparative data drawn from the dissertation indicated a reduction in maximum battery temperature from 46°C to 41°C following cooling-system optimization. Average temperature decreased from 37°C to 34.5°C, while pressure drop was reduced from 96 Pa to 72 Pa. These values suggest that improved airflow pathways may provide better heat removal with reduced flow resistance. Nevertheless, the comparison cannot be regarded as a verified numerical finding until the underlying CFD simulation files and boundary conditions have been examined.

The research also demonstrated the value of CFD as a design methodology. Numerical analysis makes it possible to investigate internal airflow behavior, identify poorly cooled regions, and compare alternative configurations before manufacturing a physical prototype. This capability is particularly useful in compact battery modules, where experimental access to internal flow passages may be limited.

The principal contribution of the paper is a structured approach to evaluating airflow optimization through thermal and pressure-based performance indicators. Future work should incorporate transient battery heat generation, multiple operating conditions, experimental validation, and detailed fan-power analysis. These investigations would provide a stronger foundation for assessing the practical suitability of optimized air-cooling arrangements.

In conclusion, airflow optimization represents a promising strategy for improving the thermal management of lithium-ion battery modules. Its effectiveness should be established through validated CFD results and realistic operating conditions before broader claims are made regarding battery safety, service life, or vehicle-level energy efficiency.

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