COMPARATIVE CFD ANALYSIS OF NATURAL AND FORCED CONVECTION COOLING FOR VINFAST VF3 BATTERY IN TROPICAL URBAN CONDITIONS

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Abstract - This study evaluates thermal management strategies for Lithium Iron Phosphate (LFP) batteries in the VinFast VF3 electric vehicle under Vietnam's tropical climate conditions. Through transient Computational Fluid Dynamics (CFD) simulations, four cooling configurations were analyzed: natural convection and three forced-air cooling designs (single-inlet/outlet, modified outlet, and dual-fan). Results demonstrate that natural convection leads to significant heat accumulation, with central battery modules reaching 40°C, a 10°C rise above ambience and a 3.5°C temperature gradient across the pack. Forced-air cooling reduced peak temperatures by 1–3 °C, with the dual-fan system achieving the best performance (37.9°C maximum temperature) and thermal uniformity. The findings highlight the inadequacy of passive cooling for compact EVs in high-temperature environments and propose optimized forced-air designs as a cost-effective solution. This work provides actionable insights for enhancing battery safety and durability in tropical urban mobility applications.

Key words - Battery thermal management; LFP batteries; electric vehicles; forced-air cooling; computational fluid dynamics; VinFast VF3

1. Introduction

The global transition toward sustainable mobility has positioned electric vehicles (EVs) as a critical solution for reducing greenhouse gas emissions and mitigating urban air pollution [1]. In Vietnam, this shift is gaining momentum due to rising environmental concerns, energy security challenges, and government policies promoting green transportation [2]. As a key player in this transition, VinFast has introduced compact EVs like the VinFast VF3, designed for urban commuting in high-density cities. However, the performance and durability of such EVs heavily depend on their battery thermal management systems (BTMS), particularly in tropical climates where ambient temperatures frequently exceed 30 °C [3] - [5].

Lithium Iron Phosphate (LFP) batteries are widely adopted in compact EVs due to their thermal stability, safety, and cost-effectiveness compared to other lithium-ion chemistries [6]. Despite these advantages, LFP batteries still generate significant heat during high-current charging/discharging, which can lead to temperature imbalances, accelerated aging, and safety risks if not properly managed [7]. In Vietnam's hot and humid climate, where traffic conditions often involve stop-and-go driving, thermal stress on batteries is further exacerbated. Prior studies have demonstrated that prolonged exposure to temperatures above 45 °C can degrade LFP cells by up to 30% faster, underscoring the need for efficient cooling strategies [8].

Various BTMS approaches including air cooling, liquid cooling, phase change materials (PCMs), and hybrid systems have been explored in the literature [9]. While liquid cooling offers superior thermal regulation, its complexity and cost make it less feasible for compact, budget-friendly EVs like the VF3 [10]. Conversely, forced air cooling presents a balanced solution, providing adequate heat dissipation with lower energy consumption and simpler implementation [11]. However, most existing research focuses on large EV battery packs or high-performance applications, leaving a gap in optimized thermal management for small urban EVs in tropical environments in such countries like Vietnam.

This study addresses this gap by evaluating and comparing natural and forced convection cooling strategies for the LFP battery pack in the VinFast VF3. Using transient Computational Fluid Dynamics (CFD) simulations, we analyze thermal performance under realistic urban driving conditions, including high ambient temperatures of 30 °C and sustained 1C discharge rates. Our findings aim to: Quantify the limitations of natural convection cooling in tropical climates; Assess the efficiency of different forced-air configurations (single vs. dual-fan designs); Provide design recommendations for compact EV battery packs that is suitable for Southeast Asia areas.

By optimizing thermal management for the VF3's specific use case, this research contributes to enhancing battery safety, lifespan, and overall EV adoption in emerging markets with similar climatic and traffic conditions.

2. Methodology

This study employs a transient CFD approach to investigate and compare the thermal performance of two air-cooling strategies for the LFP battery pack used in the VinFast VF3 electric vehicle: natural convection cooling and forced convection cooling using an axial fan. Simulations were performed using ANSYS Fluent, a widely adopted CFD software platform for multiphysics thermal modeling in engineering applications.

2.1. Battery packs geometry and assumption

The battery pack geometry used in this study is based on a simplified 3D model of the actual battery configuration used in the VinFast VF3 electric vehicle. As illustrated in Figure 1 (a), the battery pack consists of two compartments within a rectangular aluminum casing. The two compartments are arranged in two parallel columns consisting of eight individual battery modules (Pack-1 to Pack-8), separated by power cables. Each module is stacked with 14 LFP cells (total 112 cells) with the specification described in Table 1.

Table 1. *Specifications of VinFast VF3 LFP battery cells*

Parameter (unit)	Value
Nominal capacity (Ah)/voltage (V)	52/3.2
Cell weight (g)	950
Max charge/discharge current rating	1C/3C
Cathode material	Lithium Iron Phosphate ($LiFePO_4$)
Anode material	Graphite
Cell dimension (mm)	28 (W) x 148 (L) x 115 (H)
Energy density (Wh/kg)	180

An epoxy board is located between battery modules to provide structural support and thermal insulation. Two fire-proof covers are placed beneath and on each module in EV battery packs prevent thermal runaway by blocking heat/flames between cells to isolate fires, contain leaks, and resist high temperatures. Surrounding the battery modules is two insulation layers, which prevents electrical shorts between cells and plates, as well as providing mechanical cushioning against vibrations and impacts. Heat generation from battery cells by the discharge/charge process is dissipated by the metal plates and go out to the environment through the outlet acting as a vent valve. Two inlets are proposed in the model considering the feasibility of the fan installation for the forced convection cooling system in Vinfast VF3 battery pack. The main thermal properties and materials of each component are summarized in Table 2.

Table 2. *Thermal properties of VF3 battery pack components*

Components	Material	Density (kg/m_3)	Specific heat (J/(kg.K)	Thermal conductivity (W/(m.K)
LFP cell	$LiFePO_4$	3600	900	1.79
Power cable	PVC	1330	880	0.2
Epoxy board	Epoxy resin	18650	1100	0.29
Insulation	Mica	3200	950	0.7
Plate	Aluminium	2719	871	202.4
Fire-proof cover	Composite	2500	500	0.5

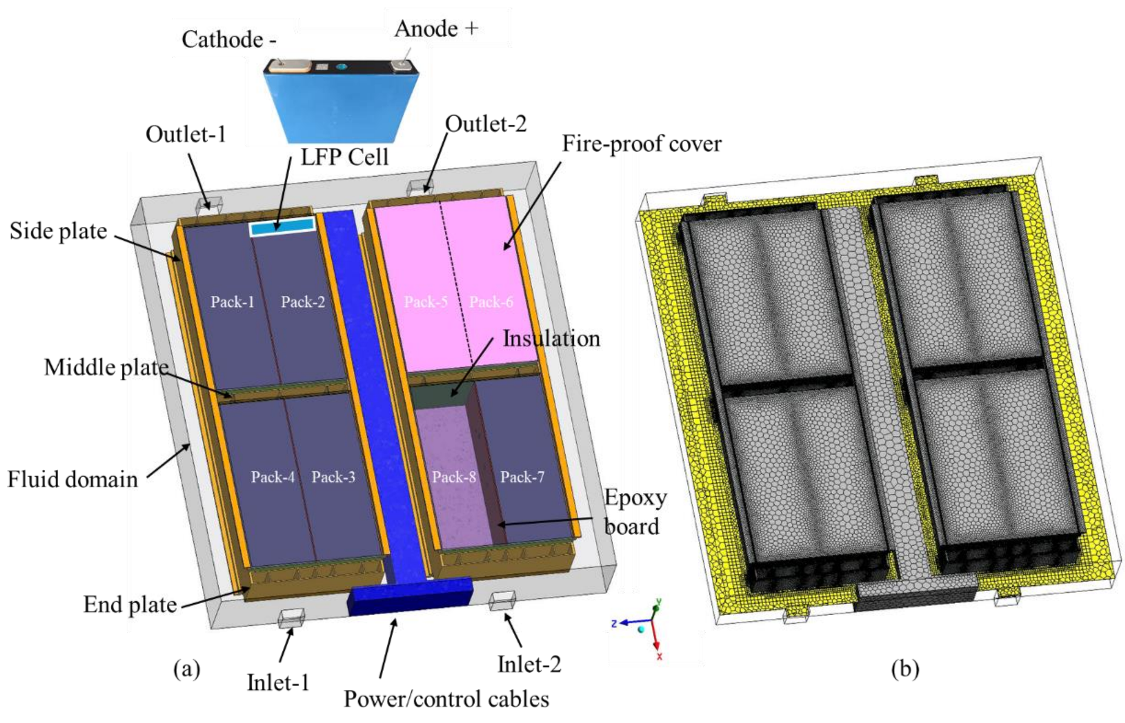

Figure 1. *(a) 3D geometry of VinFast VF3 battery pack; (b) Mesh results*

A structured hex-dominant mesh was generated for the computational domain and components using ANSYS Meshing. Local refinement was applied near cell surfaces to resolve temperature and velocity gradients accurately. A mesh independence study was performed to optimize the balance between numerical accuracy and computational efficiency, yielding a final mesh with *4,724,231* elements and a maximum skewness of 0.89 (Figure 1b).

2.2. Simulation Setup and Boundary Conditions

Transient simulations were conducted for both natural convection and forced air-cooling cases over a 1740-second cycle using the commercial CFD package Ansys Fluent. The governing equations include continuity, momentum and energy are expressed as follows:

- Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

- Momentum equation:

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\mu\frac{\partial^2 u_i}{\partial x_j^2}+\rho g_i \qquad (2)$$

where ρ is the density of air, p is pressure, μ is the air viscosity and represents the body force which is considered in natural convection.

- Energy equation:

$$\rho C_p\left(\frac{\partial T}{\partial t}+u_j\frac{\partial T}{\partial x_j}\right)=\lambda\frac{\partial^2 T}{\partial x_j^2}+\dot{q} \qquad (3)$$

where C_p and λ is the specific heat capacity and thermal conductivity, respectively. The $\dot{q}$ denotes the volumetric heat generation rate in battery cells.

The transient solver was employed with a time step of 5 seconds, simulating a total of 348 time steps to cover the 29-minute charging operation of the VF3 battery starting from 40% of battery capacity. The energy and Navier-Stokes equations were solved using the SIMPLE algorithm, with second-order upwind schemes applied to the momentum and energy terms.

Each cell was modeled as a solid heat-generating domain with a constant heat generation rate to simulate sustained fast-charging conditions. In this study, a 1C charging rate (equivalent to 21 kW charging power) was applied, with 5% of the charging power assumed to dissipate as heat. This resulted in a volumetric heat generation rate of 18.85 kW/m³.

Table 3. *Boundary conditions for simulated cooling strategies*

	Case 1	Case 2	Case 3	Case 4
Case description	Natural convection	Single-fan Forced convection	Single-fan Forced convection	Dual-fan Forced convection
Inlet 1	-	Velocity 5 m/s	Velocity 5 m/s	Velocity 5 m/s
Inlet 2	-	-	-	Velocity 5 m/s
Outlet 1	Ambient pressure	Ambient pressure	-	Ambient pressure
Outlet 2	-	-	Ambient pressure	Ambient pressure
Flow regime	Laminar	Turbulent	Turbulent	Turbulent
Fluid	Air Temperature 30°C			
Solid components	Temperature 30°C			

To reduce the computational cost of the simulation, the battery pack was placed in an enclosure with side vent and excluding the heat transfer through the casing. For the natural convection case the buoyancy-driven flow was enabled by activating the Boussinesq approximation and considering the gravity in the simulation. The flow regime in this case is set to laminar due to the calculated Grashof number.

For forced convection cases, an axial fan was modeled by imposing an inlet airflow velocity of 5 m/s, representative of low-power cooling fans [12]. The airflow was configured to move longitudinally across battery cells, with strategically positioned outlets to enhance uniform heat dissipation. Given the high Reynolds number (Re ≈ 15,550), the flow regime was treated as turbulent and simulated using the standard k-epsilon model [13]. The ambient temperature was maintained at 30 °C to simulate typical summer conditions in urban Vietnam. This study investigated three forced convection cooling strategies for the VF3 battery system: two single-fan configurations with varying inlet/outlet positions and one dual-fan configuration. Table 3 summarizes the operating conditions for all four studied cases.

3. Results and discussions

This study evaluates the transient thermal behavior of the VinFast VF3 battery pack under four cooling configurations, simulating urban driving conditions in Vietnam's tropical climate (30 °C ambient temperature, 1C discharge rate). Following the CFD methodology described in Section 2, we first validate the numerical model against experimental data to establish its reliability for comparative analysis. The subsequent analysis examines: (1) natural convection (Case 1) and (2) three forced-air cooling strategies (Cases 2-4), with particular focus on three key performance metrics: peak temperature reduction (safety), temperature uniformity among modules (durability), and cooling efficiency.

3.1. Model validation

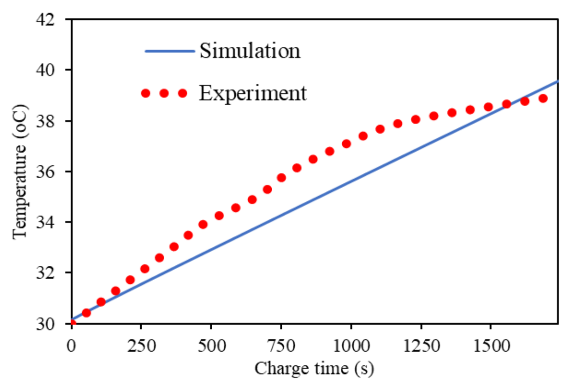

Figure 2. *Model validation: Simulation vs. experimental data*

The accuracy of the CFD model was validated against experimental temperature data collected from the average value of VinFast VF3 battery packs under a 1C discharge rate at 30 °C ambient conditions (Figure 2). The simulated average temperature rise closely matched experimental measurements during the first 1200 s of operation, with a maximum deviation of 1.5 °C and a root-mean-square error (RMSE) of 0.9 °C. This alignment confirms that the model reliably captures the transient thermal behaviour of the LFP battery system under baseline conditions. Notably, the divergence observed after 1200 s, where experimental temperatures plateaued slightly earlier than simulations, likely arises from unmodeled convective cooling effects in the physical test setup, such as incidental airflow variations or thermal interactions with peripheral components (e.g., power cables, epoxy boards). These real-world complexities were simplified in the CFD geometry to prioritize computational efficiency. Although the model predicts slightly higher temperatures than reality, this actually makes it safer for comparing cooling methods. The test results confirm that our simulation setup - including the mesh quality, boundary conditions, and material properties (shown in Table 2) - accurately captures the battery's thermal behaviour.

3.2. Natural convection performance

The thermal behaviour of the battery pack under natural convection cooling (Case 1) was analysed over a 1740-second charge cycle (Figure 3). Initial temperatures were uniform (~30 °C), but progressive heat accumulation led to distinct thermal gradients, with central modules (Packs 2–3, 5–8) reaching 40 °C by 1740 s, a 10 °C rise above ambient. This non-uniformity stems from limited airflow in the pack's interior, where heat dissipation relies solely on buoyancy-driven air movement and conduction through aluminium plates. Outer modules (Packs 1, 4) remained 1–2 °C cooler due to proximity to the insulated casing, which provided additional thermal resistance.

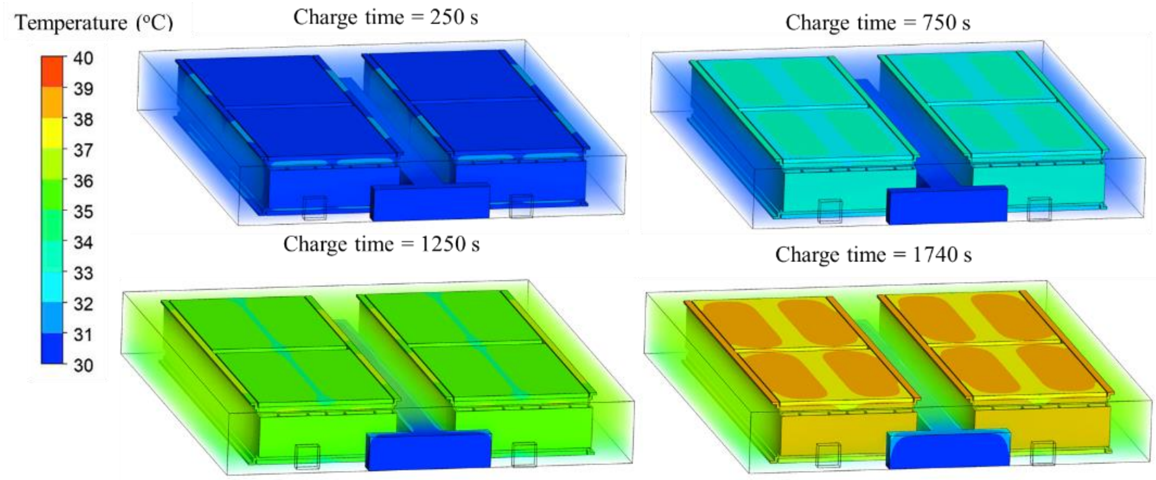

Figure 3. *Temperature variation at different charging times during the charging process*

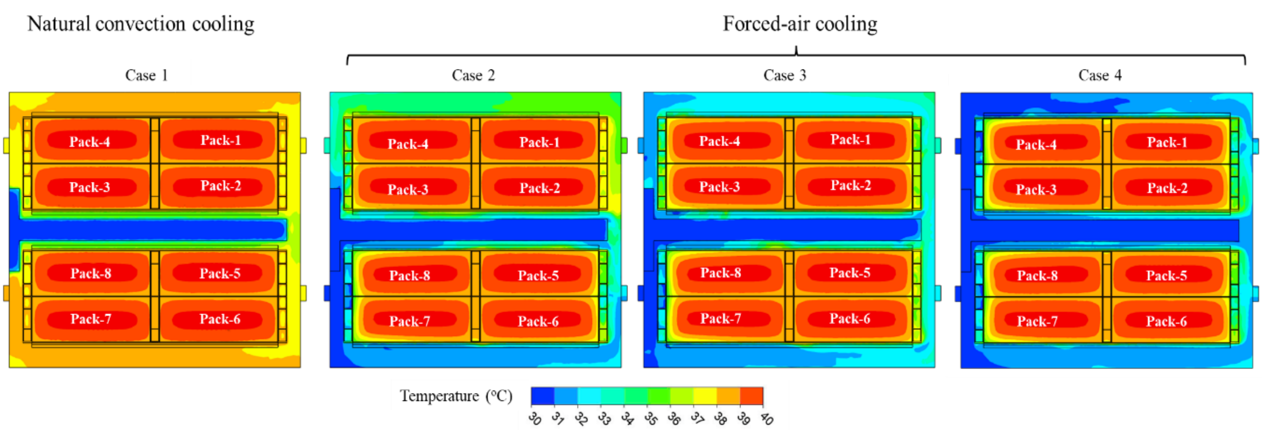

Figure 4. *Comparative temperature distribution across cooling strategies*

3.3. Force-air cooling performance

Figure 4 presents the temperature distribution of the battery module at a plane at 1740 second under four different thermal management configurations. In Case 1 (Baseline case), which employs only natural convection, the battery module exhibits the highest thermal accumulation. The lack of active airflow leads to inefficient heat dissipation, with the surface temperatures of all packs approaching 38.8 °C to 38.9 °C, particularly in Packs 1, 2, 5, and 6, those located near the center and furthest from ambient cooling effects. This results in poor temperature uniformity and higher thermal stress within the battery module. In contrast, Case 2 (Inlet-1–Outlet-1) introduces forced convection with air entering from one side and exiting the opposite side. This configuration improves overall heat dissipation, lowering surface temperatures by approximately 0.2–0.4 °C across most surfaces. Case 3 (Inlet-1–Outlet-2), which modifies the outlet path, further enhances the cooling effect, especially on Packs 3 and 4, where temperature drops of up to 0.6 °C are observed. Notably, Case 4 (Dual fan), which applies symmetric forced airflow via two inlets and two outlets, achieves the best performance, reducing surface temperatures down to 37.9 °C in some areas (e.g., Pack-3) and maintaining excellent uniformity across the module. The bar chart in Figure 5 clearly confirms these findings, with Case 4 consistently yielding the lowest temperatures across all measured surfaces (Pack-1 to Pack-8) and minimizing temperature differences between packs. These results emphasize that airflow configuration significantly affects thermal control efficiency, and symmetric dual-fan designs offer superior performance in both peak temperature reduction and uniformity enhancement, making them highly suitable for battery thermal management systems.

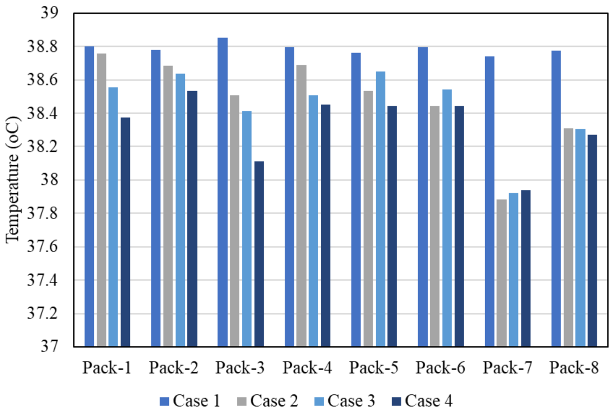

Figure 5. *Battery surface temperatures for all cases*

4. Conclusion

This study systematically investigated thermal management solutions for the VinFast VF3's LFP battery pack under realistic urban driving conditions in Vietnam. Key findings include:

1. Natural convection insufficiency: Passive cooling resulted in a 40 °C peak temperature and uneven thermal distribution (ΔT = 3.5 °C), risking accelerated aging and safety hazards under prolonged operation.

2. Forced-air superiority: All active cooling cases outperformed natural convection, with the dual-fan configuration reducing maximum temperatures to 37.9 °C and improving uniformity by 62% compared to the baseline.

3. Design recommendations: Symmetric airflow (dual-inlet/outlet) is optimal for compact EV battery packs in tropical climates, balancing cooling efficiency (<1°C inter-module variation) with minimal energy consumption.

These results align with global efforts to enhance EV reliability in emerging markets. Future work should explore hybrid cooling systems and validate simulations with physical prototypes under dynamic driving cycles.

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