

# Thermal Analysis of an Effective Hybrid Thermal Management System for a Two-Wheeler Electric Vehicle Using Computational Fluid Dynamics

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## ABSTRACT

Battery thermal management in two-wheeler electric vehicles is limited by compact battery configurations and high ambient operating conditions. This study presents a Computational Fluid Dynamics (CFD)-based thermal analysis of a hybrid Battery Thermal Management System (BTMS). The system consists of a 1 kWh lithium-ion battery pack, comprising 112 cells arranged in a 14×8 configuration, operating at an ambient temperature of 35.7 °C under a 1 C charging rate. Four different configurations are studied: (a) including a battery pack in a conventional mild steel enclosure, (b) an aluminum enclosure with fins and battery cooling fans, (c) an aluminum enclosure with fins, battery cooling fans, and enclosure cooling fans, and (d) a hybrid configuration integrating fins, cooling fans, heat sinks, and a solid-state thermoelectric chiller. The simulations are performed in ANSYS Fluent. The results show that the baseline mild steel enclosure leads to a maximum temperature of 79.22 °C, exceeding safe operating limits. The proposed hybrid configuration achieves the best performance, reducing the maximum temperature to 39.9 °C and maintaining a temperature difference of within 5 °C. The findings demonstrate that hybrid cooling significantly improves thermal performance and ensures safe operation of compact battery systems.

**Keywords**-aluminum battery enclosure; enclosure cooling; hybrid thermal management; two-wheeler battery cooling; ANSYS Fluent

## I. INTRODUCTION

High-energy-density systems (e.g., lithium-ion batteries, electric vehicle powertrains, compact electronic devices) require efficient thermal management. Traditional cooling methods, air- or liquid-based, do not offer a homogenous temperature distribution at high temperatures. Hybrid Thermal Management Systems (HTMS) that combine two or more cooling methods have received great attention. CFD is an important solution in the evaluation and optimization of such hybrid systems. Authors in [1, 2] supported that adding heat pipes to Phase Change Material (PCM) increases heat conductivity and reduces the thermal resistance in battery modules.

Geometric optimization of hybrid cooler parts through CFD can also be applied to thermal management. The best channel layouts offer a better solution to the distribution of the coolant and decrease temperature gradients between the cells [3].

Authors in [4] indicated that using hybrid systems of PCM, coupled with forced-air cooling, was superior to conventional air cooling. Specifically, cell temperatures were maintained within safe operating limits when the systems operated in aggressive discharge conditions. The parametric studies that were carried out using CFD indicated that the flow velocity, PCM thickness, and placement are important to the overall thermal performance.

Efficient hybrid systems with the use of heat pipes, liquid cooling, and an electrothermal coupling model have been explored. In [5], CFD simulations were performed utilizing electrochemical models, and the heat release and temperature change were properly predicted under the actual driving cycles. Detailed numerical simulations revealed that hybrid heat-pipe-aided systems are effective in decreasing the peak temperature and increasing the uniformity of the temperature throughout

large battery packs [6, 7]. Multi-mode cooling strategies focus on CFD as an important optimization method [8].

Furthermore, thermal management can employ hybrid systems that include immersion cooling, nanofluids, and porous media. L-shaped heat pipes with liquid cooling were analyzed by CFDs with enhanced heat removal and structural flexibility in small-scale battery modules [9]. Numerical and experimental studies on hybrid liquid-air systems proved that the latter have better cooling performance than the single-mode systems [10]. CFD optimization of flat heat pipe systems also increased the efficiency of heat transfer and reduced thermal non-uniformity [11]. According to the CFD results from [12], immersion cooling using nanofluid is effective as it leads to better convective heat transfer and elimination of hotspots. Systems based on the hybrid combination of PCM and active cooling have been studied to lengthen thermal buffering capacity and be operationally stable [13].

Authors in [14, 15] highlighted the optimization of hybrid PCM-liquid cooling systems based on optimistic numerical procedures of CFD. Significant decreases were observed in the maximum temperature and pressure drop through parametric and multi-objective optimization research. CFD of immersion-based hybrid cooling systems provided encouraging results for next-generation battery packs [16]. Also, combined systems of thermoelectric components and nanofluids were developed with improved thermal control, especially in varying load conditions [17].

Passive HTMS based on PCM and metal foam architecture demonstrated better heat uptake and uniformity of thermal fields without additional energy cost [18]. Authors in [19] summarized the progress in PCM- and nanofluid-based hybrid systems through CFD-based optimization. Moreover, the use of multi-objective optimization of hybrid liquid cooling systems with the help of CFD revealed that this battery optimization method was applicable to high-power electronics and energy systems [20]. Hybrid designs combining PCM, porous fin, with a liquid cooling structure resulted in excellent thermal characteristics without increasing size [21].

Combining multiple cooling techniques, such as air, liquid, and thermoelectric systems, provides superior performance compared to single-mode cooling approaches [22]. Authors in [23] conducted experimental and CFD studies and confirmed that hybrid cooling improves heat dissipation and maintains safe operating temperatures. Additionally, optimized hybrid configurations reduce temperature gradients and improve thermal stability [24]. Under high ambient conditions, hybrid systems effectively control temperature rise in compact battery modules [25].

This study focuses on a compact hybrid BTMS designed specifically for two-wheeler electric vehicle battery packs operating under high ambient temperature conditions. A detailed CFD-based thermal analysis of four different configurations, including a baseline mild steel enclosure and three aluminum-based hybrid cooling setups, is carried out using ANSYS Fluent simulation software. A systematic comparison of conventional and hybrid cooling approaches is then performed in terms of maximum temperature ( $T_{max}$ ) and

temperature difference ( $\Delta T$ ). The proposed hybrid configuration integrating fins, forced air cooling, heat sinks, and a solid-state thermoelectric chiller demonstrates significant improvement in thermal performance and temperature uniformity. Finally, the study shows that the hybrid BTMS maintains the battery temperature within the safe operating range and achieves  $\Delta T < 5^\circ\text{C}$ , making it suitable for compact electric vehicle applications.

## II. METHODOLOGY

### A. Battery Pack Modeling and Two-Wheeler BTMS

In this study, 112 lithium-ion cells are used to design a battery module of 1 kWhr capacity. The cells are arranged in an aligned manner in two stacks with 14x4 cells in each stack. The battery pack is placed in a mild steel enclosure and an aluminum casing of dimensions 196x200x466 mm with the proposed cooling arrangement in 4 setups to test its thermal conductivity. The battery pack model, as presented in Figure 1, is designed in 3D-CAD software for its thermal analysis using ANSYS® Fluent.

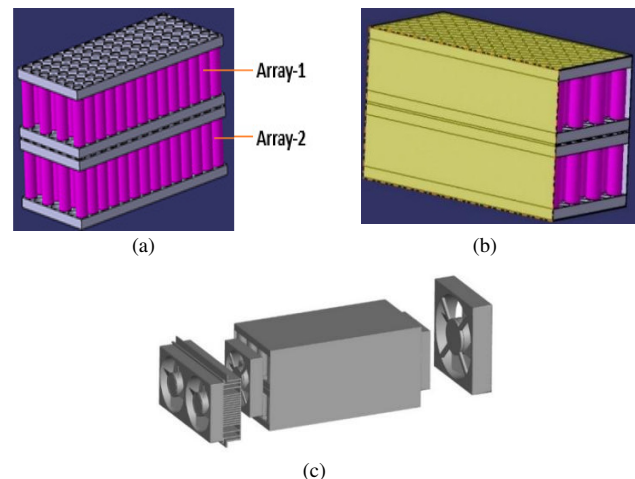


Fig. 1. The battery pack model: (a) battery enclosure, (b) battery enclosure in a mild steel enclosure, and (c) battery enclosure with all the cooling arrangements integrated.

The setup for each cooling arrangement is:

1. Setup 1: Battery module placed in a conventionally used mild steel enclosure.
2. Setup 2: Battery module placed in an aluminum enclosure with fins and battery cooling fans to facilitate continuous cooling within the battery pack with natural cooling.
3. Setup 3: Battery module placed in an aluminum enclosure with fins, battery cooling fans, battery cooling, and enclosure fans, and both running.
4. Setup 4: Battery module placed in an aluminum enclosure with fins, battery cooling fans, enclosure cooling fans with heat sinks, and solid-state chillers all working together for efficient heat transfer to the atmosphere when the vehicle is charging.

### B. BTMS Thermal Analysis

The battery pack, along with its enclosure and cooling arrangements, is meshed using a Poly-Hexacore element type, comprising a mesh of 5.1 million elements with a maximum skewness of 0.86, as illustrated in Figure 2.

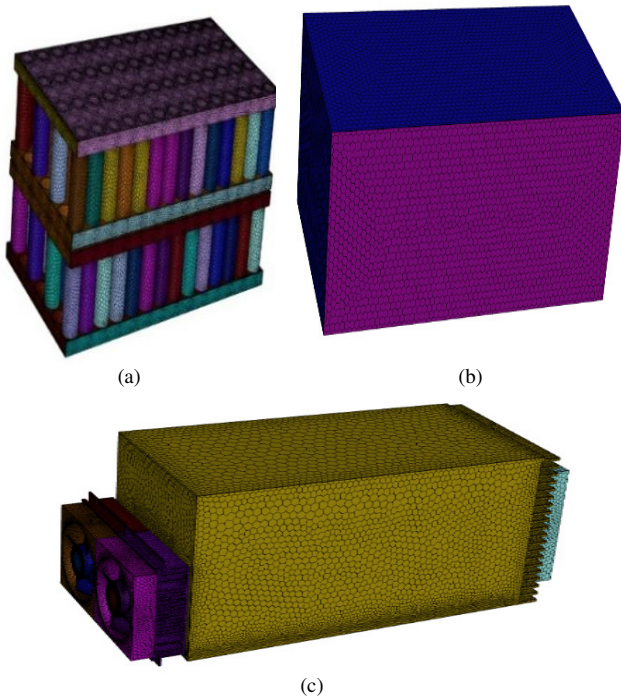


Fig. 2. (a) Meshing of battery pack, (b) meshing of enclosure, and (c) outer view of meshing of battery pack and its enclosure with combined cooling arrangement.

### C. Mesh Independence Study

A mesh independence study is carried out to ensure that the simulation results are not affected by mesh size. Three different mesh densities are considered: coarse, medium, and fine.  $T_{max}$  is used as the evaluation parameter. The results indicate that the variation in  $T_{max}$  between the medium mesh and fine mesh is negligible. Therefore, the medium mesh consisting of approximately 5.1 million elements is selected for the simulations, due to its balance between computational accuracy and efficiency. The mesh quality is also evaluated in terms of skewness and orthogonality, which are found to be within acceptable limits for accurate CFD analysis.

### D. Battery Cell Specifications

The battery pack consists of cylindrical lithium-ion cells arranged in a 14×8 configuration. Each cell is assumed to be of standard cylindrical format with a nominal capacity of between 2.5 and 3 Ah. The dimensions of each cell are 18 mm in diameter and 65 mm in height. The internal resistance of the cell is considered constant for the 1 C charging condition. The thermal properties of the cell are modeled as anisotropic, with higher thermal conductivity in the radial direction compared to the axial direction. The values used in this study ( $K_x = K_y = 20$  W/m-K and  $K_z = 0.6$  W/m-K) are consistent with commonly reported data for cylindrical lithium-ion cells.

### E. Thermophysical Properties of Materials

Table I presents the thermophysical properties of the solid materials used in the simulation, including lithium-ion cells, mild steel, aluminum, Acrylonitrile Butadiene Styrene (ABS), a solid-state chiller, and thermal grease. The lithium-ion cells are modeled with anisotropic thermal conductivity to capture directional heat transfer characteristics, while other materials are considered isotropic with constant properties.

TABLE I. SOLID PROPERTIES

Material	Density (kg/m <sup>3</sup> )	Specific heat (J/kg-K)	Thermal conductivity (W/m-K)
Lithium-ion	2300	1100	$K_x=K_y=20, K_z=0.6$
Mild steel	8030	502.48	16.27
Aluminum	2719	871	202.12
ABS	1070	1300	0.17
Solid state chiller	7500	200	1.75
Thermal grease	2400	700	2

Table II summarizes the properties of air used as the working fluid in the analysis. Air is modeled as an incompressible fluid with constant density, specific heat, thermal conductivity, and viscosity, which are required to accurately simulate convective heat transfer within the battery enclosure.

TABLE II. PROPERTIES OF THE AIR AS WORKING FLUID

Density (kg/m <sup>3</sup> )	Specific heat (J/kg-K)	Thermal conductivity (W/m-K)	Viscosity (Pa-s)
$1225 \times 10^{-3}$	$1.0064 \times 10^3$	$24.2 \times 10^{-3}$	$0.179 \times 10^{-6}$

### F. Numerical Settings for Thermal Analysis

The simulations are carried out utilizing a pressure-based steady-state solver in ANSYS Fluent. The pressure-velocity coupling is achieved through the SIMPLE algorithm. Second-order upwind discretization schemes are applied for momentum and energy equations to ensure numerical accuracy. Appropriate under-relaxation factors are used to maintain numerical stability during the solution process. The convergence criteria are defined such that the residuals of all governing equations fall below  $10^{-5}$ . In addition, temperature is monitored to ensure solution convergence. Buoyancy effects are included in accounting for natural convection within the enclosure. Air is modeled as an incompressible fluid with constant properties. The conservation of mass or continuity equation is presented by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot u) = 0 \quad (1)$$

where  $\rho$  is the fluid density,  $t$  is the time, and  $u$  is the velocity vector. The conservation of momentum equation is:

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{\nabla p}{\rho} + \nu \nabla^2 u + f_g \quad (2)$$

where  $p$  is the static pressure,  $\nu$  is the viscosity, and  $f_g$  represents the body forces, typically gravity. The conservation of energy equation is shown by:

$$\frac{\partial (\rho h_{total})}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot (\rho \cdot u \cdot h_{total}) =$$

$$\nabla(\lambda \nabla T) + \nabla(u \cdot t) + Q_E \tag{3}$$

where  $h_{total}$  is the total enthalpy,  $\lambda$  is the conductivity,  $T$  is the temperature, and  $Q_E$  are the external sources of energy.

G. Heat Generation Model

The heat generated within lithium-ion cells during charging is modeled based on Joule heating. Under 1 C charging conditions, the heat generation is calculated using:

$$Q = I^2 R \tag{4}$$

where  $Q$  is the heat generation,  $I$  is the current, and  $R$  is the internal resistance of the cell. The generated heat is assumed to be uniformly distributed within the cell volume and is applied as a constant volumetric heat source in the CFD model. This assumption is commonly used in pack-level thermal analysis, where detailed electrochemical effects are not explicitly considered.

III. BOUNDARY CONDITION

The simulations are carried out at an ambient temperature of 35.7 °C and an operating pressure of 101325 Pa. Air is considered an incompressible fluid with constant properties. The battery cooling fans are modeled with velocity-inlet and pressure-outlet boundary conditions. The inlet airflow is specified based on the fan characteristics, while the outlet is defined as a pressure outlet with zero-gauge pressure. Turbulence intensity is specified at the inlet to account for turbulent flow conditions. The standard  $k-\epsilon$  turbulence model is used, with buoyancy effects included, to account for natural convection driven by temperature gradients. All solid walls are treated with no-slip boundary conditions, and heat transfer between solid and fluid domains is considered. The expanded view of designed BTMS is presented in Figure 3.

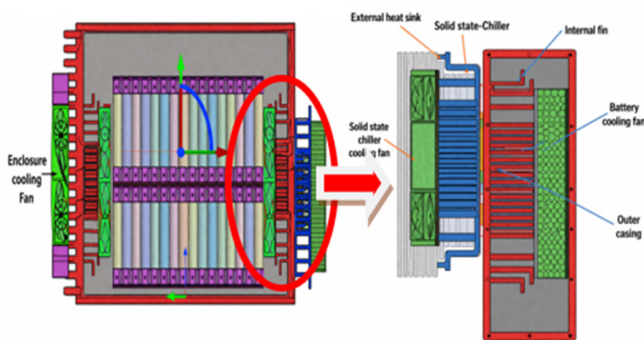


Fig. 3. Insight view of battery pack structure with the designed BTMS and its expanded view.

IV. RESULTS AND DISCUSSION

The thermal analysis for the designed battery pack for a two-wheeler electric vehicle is performed using ANSYS Fluent at 35.7 °C ambient temperature when charged at 1 C charge rate to know the  $T_{max}$  of cell arrays inside the battery enclosure assembly for all configurations. The results are presented in Figures 4-8.

1. Setup 1: Thermal analysis of the battery pack placed in a mild steel enclosure.
2. Setup 2: Thermal analysis of the battery pack placed in an aluminum enclosure with fins and battery cooling fans.
3. Setup 3: Thermal analysis of the battery pack placed in an aluminum enclosure with fins, battery cooling fans, and enclosure cooling fans with heat sinks.
4. Setup 4: Thermal analysis of the battery pack placed in an aluminum enclosure with fins, battery cooling fans, enclosure cooling fans with heat sinks, and solid-state chillers for efficient heat transfer.

From the temperature contours of cells in Array-1 and Array-2, the observed  $T_{max}$  is 79.22 °C ( $\Delta T=44.2$  °C) in Setup 1,  $T_{max}$  is 44.27 °C ( $\Delta T=8.57$  °C) in Setup 2,  $T_{max}$  is 43.38 °C ( $\Delta T=7.68$  °C) in Setup 3, and  $T_{max}$  is 39.9 °C ( $\Delta T=4.2$  °C) in Setup 4. These  $T_{max}$  and  $\Delta T$  values from all four setups validate that the battery pack with Setup 4 is most effective ( $\Delta T=4.2$  °C, less than 5 °C), during hot summers where average ambient air temperature is 35.7 °C compared to the battery pack placed in a conventionally used mild steel enclosure.

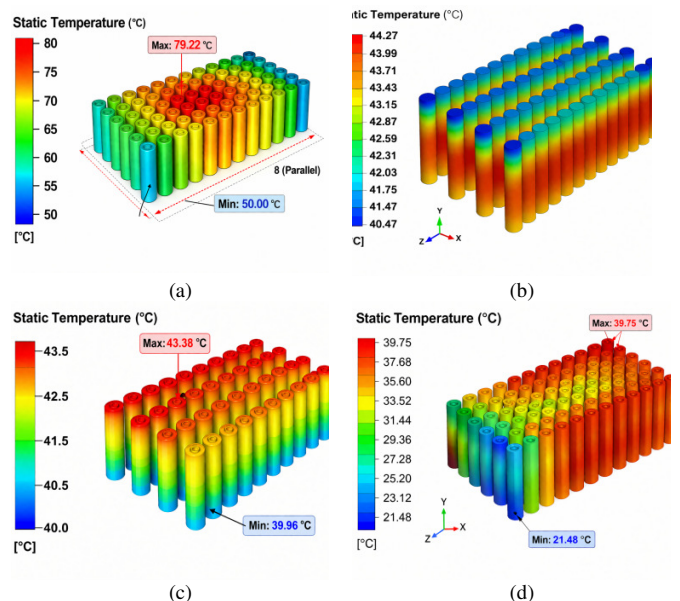


Fig. 4. Static temperature contours of cells in Array 1 for (a) Setup 1, (b) Setup 2, (c) Setup 3, and (d) Setup 4.

Table III provides a comparative analysis of  $T_{max}$  for all four setups at an ambient temperature of 35.7 °C under a 1 C charging rate. The results reveal a significant reduction in temperature from Setup 1 to Setup 4. The baseline mild steel enclosure (Setup 1) exhibits the highest temperatures, while the hybrid configuration (Setup 4) achieves the lowest  $T_{max}$  across Array 1, Array 2, and enclosure components. This demonstrates the effectiveness of the proposed hybrid BTMS in improving thermal performance and maintaining temperature within safe operating limits.

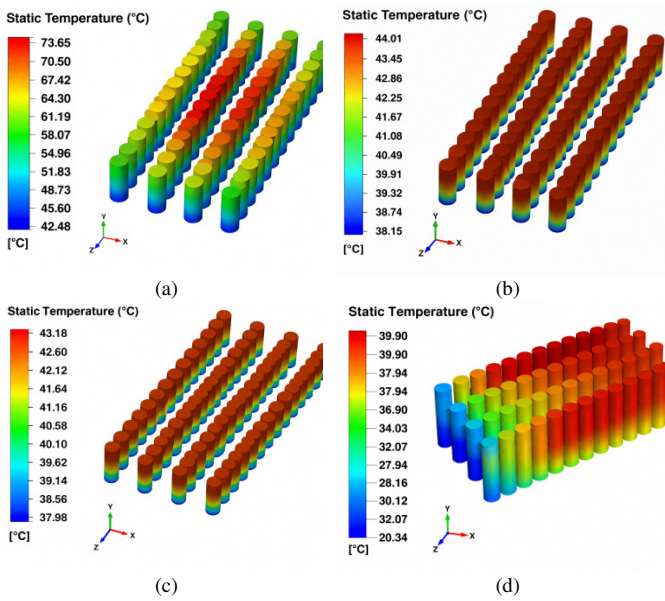


Fig. 5. Temperature contours of cells in Array 2 for (a) Setup 1, (b) Setup 2, (c) Setup 3, and (d) Setup 4.

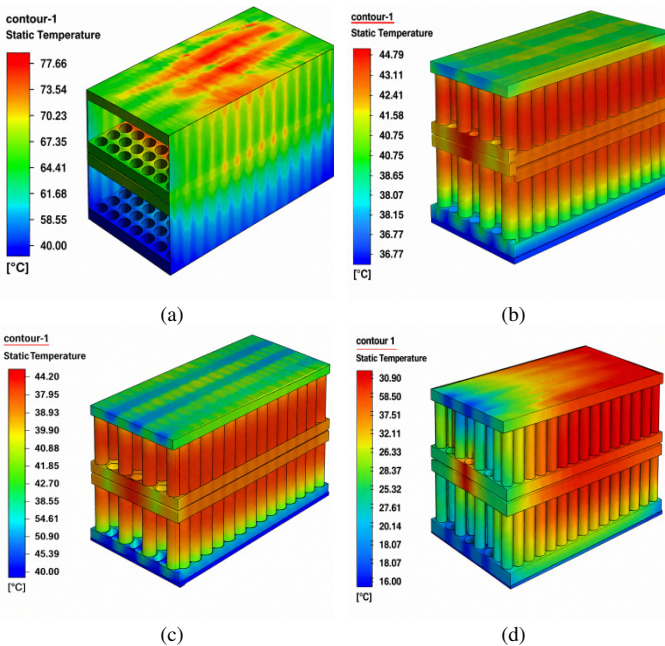


Fig. 6. Cell casing temperature for both cell arrays for (a) Setup 1, (b) Setup 2, (c) Setup 3, and (d) Setup 4.

TABLE III. COMPARATIVE ANALYSIS OF SETUPS:1-4 AT 35.7°C AMBIENT TEMPERATURE UNDER 1 °C CHARGE RATE

Setup ( $T_{max}$ in °C)	Setup 1	Setup 2	Setup 3	Setup 4
Array 1	79.22	44.27	43.38	39.76
Array 2	73.65	44	43.18	39.9
Battery enclosure	48.43	37.05	36.91	33.43
Cell enclosure	77.66	44.7	44.2	39.9

A. Model Validation

To ensure the reliability of the numerical model, the obtained simulation results are compared with available results from published literature on lithium-ion battery thermal management systems. The  $T_{max}$  values obtained in this study fall within the commonly reported range for battery packs operating under high ambient conditions and 1 C charging rates. This agreement indicates that the developed CFD model provides a reasonable prediction of thermal behavior.

B. Energy Consumption Considerations

The hybrid configuration (Setup 4) improves thermal performance but introduces additional energy consumption due to the cooling fans and the thermoelectric chiller. While forced convection enhances heat transfer, it requires fan power, and the chiller further increases energy demand. Thus, a trade-off exists between thermal performance and energy efficiency. The achieved reduction in  $T_{max}$  and improved uniformity justifies the additional power consumption, particularly for ensuring battery safety and longevity.

V. CONCLUSION

This study presents a Computational Fluid Dynamics (CFD) based thermal analysis of a hybrid Battery Thermal Management System (BTMS) for a two-wheeler electric vehicle battery pack operating under high ambient conditions. The study addresses the challenge of maintaining safe operating temperatures and thermal uniformity in compact battery configurations where conventional cooling is insufficient.

Four configurations were analyzed. In Setup 1, the mild steel enclosure results in a high temperature of 79.22 °C, exceeding safe limits. Replacing it with an aluminum enclosure in Setup 2 improves heat dissipation due to higher thermal conductivity, but overheating persists (44.27 °C). Setup 3, with additional forced cooling, shows marginal improvement (43.38 °C). The proposed hybrid configuration (Setup 4), integrating fins, cooling fans, heat sinks, and a solid-state thermoelectric chiller, achieves the best performance, reducing the maximum temperature to 39.9 °C and maintaining temperature uniformity within safe limits. Compared to the baseline case, Setup 4 shows up to 50% reduction in peak temperature and ensures operation within the optimal range (15 °C–40 °C), thereby enhancing battery safety and lifespan. The results demonstrate the effectiveness and novelty of hybrid cooling strategies for compact electric vehicle battery systems. Future work will focus on experimental validation, enhancing the accuracy of the model, and optimizing energy usage.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGMENT

Not applicable to this work.

## DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

## AI USE AND DECLARATION OF GENERATIVE AI USE

The authors confirm that no generative AI tools were used in the preparation of this manuscript.

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