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***Corresponding author:**

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Evaluation of the impact of cooling regimes on battery and passenger cabin in EVs

Dong Doan Van^{1,2*}, Hue Phuoc Lu², Huu Phuoc Nguyen², Pham Nhu Nam³¹Institute of Mechanical Engineering, Ho Chi Minh City University of Transport, Ho Chi Minh City 70000, Vietnam²BRIDGE Research Group, Ho Chi Minh City University of Transport, Ho Chi Minh City 70000, Vietnam³Mechanics of Advanced Materials and Structures, University of Transport Technology, Hanoi, Vietnam

Abstract: Efficient thermal management of battery packs in electric vehicles (EVs) is critical for maintaining operational performance, ensuring safety, extending battery lifetime, and preserving passenger thermal comfort. Excessive battery temperatures accelerate degradation and increase safety risks, while aggressive cabin cooling can significantly raise energy consumption. In this study, a Model-Based Design (MBD) framework is developed to investigate the coupled thermal behavior of the battery pack and passenger cabin through a multi-domain system-level simulation integrating electrical and thermal subsystems. Three distinct thermal control strategies, prioritizing cabin cooling, battery cooling, and a balanced compromise, respectively, are evaluated under ambient temperatures ranging from 20 °C to 40 °C. The simulation results reveal pronounced trade-offs between battery temperature regulation, cabin comfort, and overall energy consumption. The balanced control strategy achieves battery temperature levels comparable to the battery-priority strategy while maintaining acceptable cabin comfort and moderate energy use. The findings demonstrate that integrated and adaptive thermal management strategies can effectively reconcile competing thermal demands, offering a promising pathway to improve EV energy efficiency, safety, and operational robustness under diverse climatic conditions.

Keywords: Energy efficiency, battery cooling, thermal management, electric vehicles, cabin comfort.

1. Introduction

As electric vehicles (EVs) become increasingly prevalent, the development of intelligent and efficient Battery Thermal Management Systems (BTMSs) has become particularly critical. The operational performance and service life of batteries are strongly dependent on their operating temperature, as temperature not only governs the rate and efficiency of electrochemical reactions within battery cells but

also directly affects the overall system stability and operational safety. Excessively low temperatures can reduce ionic conductivity and increase internal resistance, whereas excessively high temperatures may accelerate material degradation, resulting in capacity fade, reduced cycle performance, and potential risks of overheating or fire. Therefore, maintaining the battery temperature within an optimal range is a key factor in ensuring the reliability and longevity of

on-board energy storage systems in EVs [1–3]. In addition, maintaining thermal comfort in the passenger cabin without compromising battery cooling effectiveness poses a complex technical trade-off, particularly under harsh operating conditions.

According to Hwang et al. [4], the BTMS plays a pivotal role in ensuring performance, safety, and extended service life of EV battery packs. Currently, the EV industry mainly employs four types of BTMSs, including air cooling, liquid cooling, phase change materials (PCM), and thermoelectric cooling, in addition to hybrid systems that combine two or more of these approaches. Each BTMS type exhibits distinct advantages and limitations. Air cooling features low cost, light weight, and minimal maintenance requirements, but its effectiveness is limited under high thermal loads. In contrast, liquid cooling provides a high heat transfer coefficient and more uniform temperature distribution, making it suitable for large-capacity battery packs and long-range EVs; however, it increases system cost, weight, and maintenance demands. PCM-based systems can absorb a large amount of heat during the phase change process and operate passively, but they suffer from low thermal conductivity and a narrow operating temperature range. Thermoelectric cooling enables precise temperature control, yet its efficiency is insufficient for standalone application. Hybrid BTMSs leverage the advantages of multiple methods but introduce increased system complexity and cost, requiring careful consideration prior to implementation.

In the study by Bamdezh et al. [5], the carbon emissions of EVs equipped with air-based, liquid-based, and PCM-based BTMSs were analyzed under real driving conditions. Simulations were conducted on a monthly basis throughout the year with second-level resolution, accounting for variations in power demand and battery temperature, while battery aging over a 10-year period was also evaluated. The results indicated that the PCM-based system reduced energy

consumption by 14.68% and 22.71% compared with air cooling and liquid cooling, respectively. After 10 years of operation, the battery capacity degradation for PCM, air, and liquid cooling systems was 6.95%, 7.17%, and 7.26%, respectively. In terms of carbon emissions, the corresponding values were 10.042 kg, 11.241 kg, and 12.242 kg CO₂ per 100 km.

El Afia et al. [6] reported that lithium-ion batteries are the most efficient and widely used energy source for EVs; however, optimizing thermal management remains a major challenge in maintaining performance and extending battery lifespan. Simulations of a battery pack consisting of 12 cells connected in series demonstrated that full immersion cooling in a thermally conductive liquid outperformed air cooling and indirect liquid cooling, achieving reductions in temperature difference of 2.5%, 0.6%, and 1.2%, respectively. The superior thermal uniformity and high heat transfer coefficient of full immersion cooling help prevent thermal runaway and mitigate capacity degradation, indicating its strong potential despite being relatively underexplored in EV applications.

Park et al. [7] investigated the effects of driving modes and ambient temperature on battery performance, thermal management, and energy consumption in EVs equipped with heat pump systems. The results showed that extreme temperatures significantly reduced performance, with reductions of up to 67% in urban driving and 42% on highways at -15 °C, primarily due to the use of positive temperature coefficient (PTC) heaters, and reductions of 24% and 12% at 35 °C, respectively, owing to increased cooling demand. Correlation analysis revealed that the BTMS actively adjusted its operation by prioritizing heating at -15 °C and intensive cooling at 35 °C, while requiring less adjustment at 25 °C. This study highlights the necessity of optimizing both the BTMS and the air-conditioning system to improve energy efficiency and extend driving range, particularly under extreme temperature conditions.

In recent years, increasing attention has

been devoted to integrated thermal management systems for EVs, in which the BTMS and the cabin air-conditioning system are jointly controlled to improve overall energy efficiency and thermal performance [8]. Unlike conventional approaches that treat these subsystems independently, integrated frameworks enable coordinated regulation of thermal loads and energy consumption under varying operating conditions

Electric vehicle battery cooling

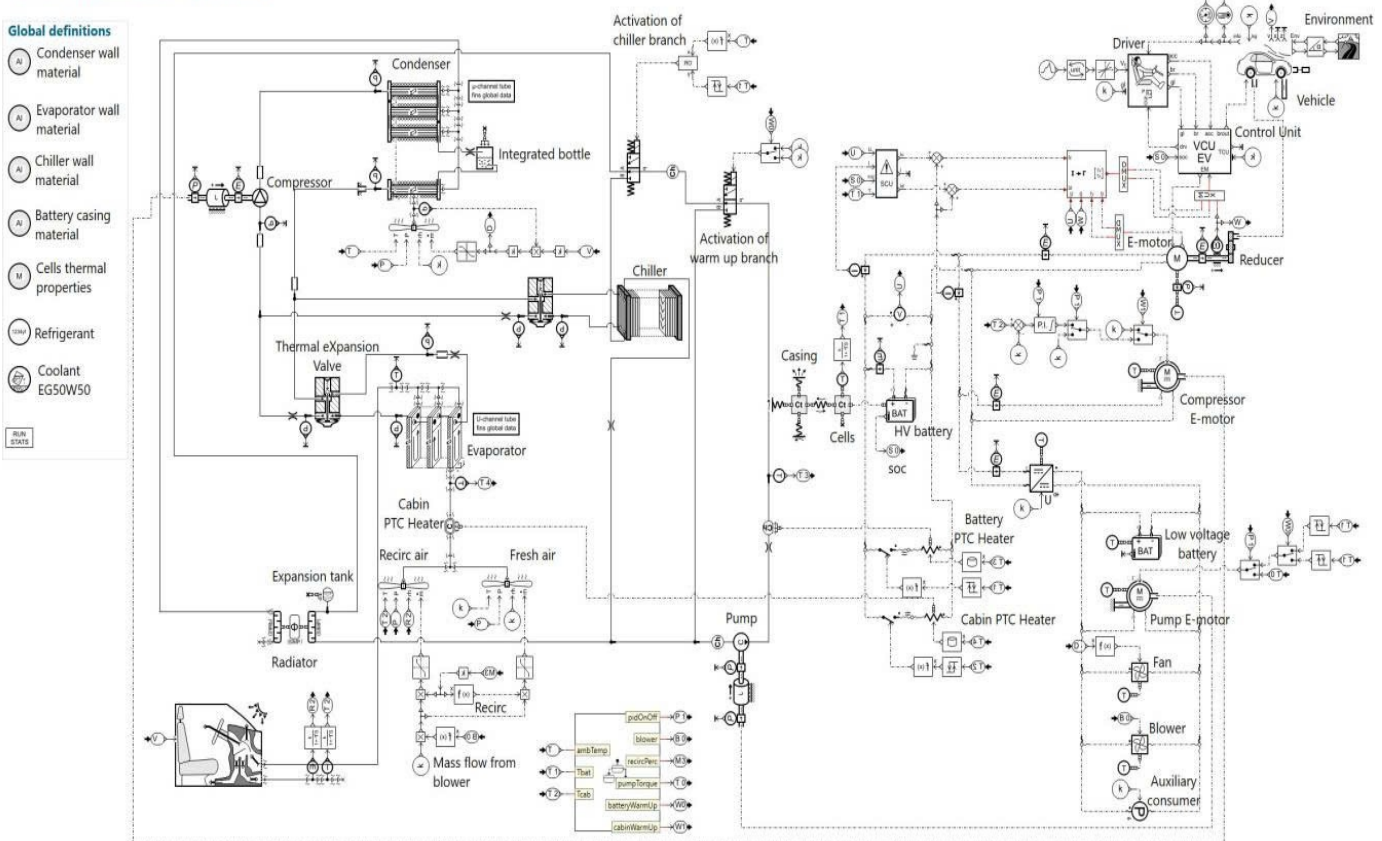


Fig. 1. Schematic diagram of the electric vehicle battery and passenger cabin cooling system

Despite these advances, system-level analyses that explicitly quantify the trade-offs among control strategies under different ambient conditions remain limited. Therefore, this study conducts simulations and analyses of three different thermal control strategies using the Amesim software. The objective is to evaluate the trade-off between battery cooling effectiveness and passenger cabin thermal conditioning, thereby identifying the key factors influencing overall thermal system performance and providing guidance for optimizing integrated BTMS configurations.

[9]. Recent studies have further explored advanced control strategies, including model-based and reinforcement learning approaches, to handle the coupled thermal dynamics of battery and cabin systems [10]. Moreover, it has been shown that the energy required for thermal management can significantly affect vehicle driving range, highlighting the importance of optimal thermal control [11].

To guide the reader through the study, the remainder of this paper is organized as follows. Section 2 describes the development of the system model in the Amesim environment, in which individual submodels are established and integrated to form a complete model. Section 3 presents the simulation results obtained for different control strategies and discusses the corresponding findings. Finally, Section 4 provides the conclusions and highlights the main implications of the results.

2. System Model Development

The simulation model is developed based on

a system-level model-based design framework, which enables tight integration between the electrical and thermal subsystems of the electric vehicle. The model structure captures the dynamic interactions among the fundamental components of the thermal management and energy distribution system. In this framework, the battery pack is represented by a two-node thermal model comprising:

The battery casing, where heat exchange with the ambient environment or the coolant takes place; and

The battery cell core, which constitutes the primary heat generation region due to electrochemical reactions.

The overall simulation architecture consists of the following functional subsystems:

A coolant loop, incorporating a radiator and a chiller, which serves as the primary mechanism for controlling battery temperature;

A refrigerant loop, shared by both the passenger cabin cooling system and the battery thermal management system;

An electric drivetrain, powered by the high-voltage battery, to represent energy consumption and heat generation during vehicle operation; and

Auxiliary components, including a centrifugal pump in the coolant loop, a radiator fan, and an evaporator blower powered by a low-voltage battery, thereby accurately reflecting the distributed energy consumption characteristics of a real-world system.

This modeling approach enables a comprehensive assessment of heat transfer performance and energy management behavior, thereby supporting the optimization of control strategies and BTMS configuration design under a wide range of operating conditions, as illustrated in Fig. 1 [12].

In this study, a compact- to mid-size urban electric vehicle fully powered by electricity is considered as the research object. Specifically, an electric vehicle model closely resembling the 2019 Nissan Leaf, one of the world's best-selling electric

vehicles, is developed and employed for the analysis [13]. All control strategies are evaluated on a straight and smooth roadway without surface irregularities, allowing the control problem to be simplified and the influence of road disturbances to be eliminated. Under these conditions, the strategies focus on longitudinal speed tracking and torque regulation, enabling a fair comparison of their performance based solely on control design.

The heating system comprises two PTC heaters. One PTC heater warms the battery pack via the coolant loop, while the other heats the passenger cabin through the humid air stream. The operation of these heaters is governed by on-off switches based on the actual temperatures of the battery pack and the passenger cabin. The driver model calculates accelerator and brake pedal position signals to track a predefined speed profile. The drivetrain controller converts the acceleration demand into the required motor torque and decomposes the braking demand into regenerative braking torque and mechanical braking torque when necessary.

In this simulation study, it is assumed that the vehicle accelerates from standstill to a steady cruising speed of 90 km/h.

The electrical system is configured around a high-voltage (HV) battery pack, which serves as the central energy source and supplies power to two electric motors with distinct functions:

The first motor drives the compressor of the air-conditioning system, which is responsible for cooling the air supplied to the passenger cabin and assisting battery cooling via the chiller.

The second motor acts as the main traction motor of the electric vehicle, converting electrical energy into mechanical power to generate longitudinal motion.

This configuration reflects the typical electrical architecture of modern electric vehicles, in which the HV battery not only supports propulsion demands but also powers high-load auxiliary systems, particularly the thermal management system, thereby improving overall

efficiency and reducing reliance on the low-voltage auxiliary system.

In addition to the HV battery pack, the system is equipped with a low-voltage (LV) battery pack that supplies energy to auxiliary devices with relatively low power demand but continuous operation requirements to maintain stable system functionality. Specifically, the LV battery powers:

The electric motor driving the centrifugal pump in the coolant loop, ensuring coolant circulation through the battery pack, radiator, and chiller.

The radiator fan, which enhances heat dissipation between the coolant and the ambient environment.

The evaporator blower, which distributes cooled air into the passenger cabin.

Other auxiliary loads, including controllers, sensors, solenoid valves, and the central processing unit.

This separation of HV and LV power sources reflects practical EV design principles, enabling efficient energy management, reducing the load on the main electrical system, and ensuring the safety and reliability of auxiliary functions.

To ensure sustainable operation and extend battery service life, the system integrates a Safety Control Unit (SCU). This intelligent control module monitors and constrains operating conditions that may pose risks to the battery, particularly during high-current charging and discharging phases. Rather than directly transmitting the driver's torque request to the electric motor, the SCU computes an equivalent torque command that enforces thermal and current safety constraints within allowable limits. This torque command is subsequently sent to the Vehicle Control Unit (VCU), which regulates the motor torque output to achieve optimal performance while maintaining battery safety under all operating conditions.

The refrigerant subsystem plays a central role in maintaining appropriate operating temperatures for both the battery pack and the passenger cabin. The humid air stream passing

through the evaporator is regulated according to vehicle speed, with a minimum airflow ensured by the evaporator blower when required. A parallel branch containing a plate-type chiller is integrated to provide additional cooling when necessary, with a thermal expansion valve (TEV) controlling the refrigerant mass flow rate.

The refrigerant used in the model is R-1234yf (1,1,1,2-tetrafluoropropene), a next-generation hydrofluoroolefin (HFO) refrigerant with a low global warming potential (GWP), intended as a replacement for R-134a. The change in refrigerant type and the addition of the chiller branch require appropriate adjustment of the refrigerant charge [14]. The coolant subsystem, incorporating a radiator, is responsible for dissipating heat from the battery pack to the ambient environment or transferring it to the chiller. Its main components include:

A hydraulic thermostatic valve for selecting the cooling source (radiator or chiller).

A centrifugal pump for regulating the coolant flow rate.

An expansion tank.

An air-cooled radiator.

A chiller connected to the air-conditioning loop.

A convective heat transfer element coupled to the battery casing.

These components operate in coordination to maintain the battery temperature within a safe operating range, particularly under high ambient temperature conditions.

The battery cells are modeled as a thermal mass with defined density, heated by internal heat generation due to electrical losses. Heat generated within the cells is transferred to the battery casing through conductive contact. The casing subsequently dissipates heat to the cooling system via convection. As the battery casing is in direct contact with the ambient air, convective and radiative heat transfer mechanisms are also taken into account in the model.

To improve model transparency and

reproducibility, the key modeling assumptions and parameters are explicitly defined. The battery heat

generation is calculated based on internal resistive losses:

Table 1. Key thermal parameters used in the simulation

Parameter	Value	Unit
Battery thermal capacity	45–60	kJ/K
Internal resistance	0.01–0.02	Ω
Battery heat transfer coefficient	20–100	W/m ² K
Cabin thermal capacity	80–120	kJ/K
Cabin heat transfer coefficient	5–15	W/m ² K
Coefficient of performance	2.5–3.5	-
Refrigerant system modeling	Amesim-based	-

$$Q_{\text{gen}} = RI^2 \quad (1)$$

where: I is the battery current, and R is the internal resistance. The thermal behavior of the system is further characterized by parameters including battery thermal capacity, internal resistance, heat transfer coefficients (battery–coolant and radiator–air), coefficient of performance, and refrigerant system modeling. A summary of these key parameters is provided in Table 1.

In this study, the performance evaluation is conducted based on three thermal control strategies:

Strategy 1: Priority given to passenger cabin cooling. The comfort zone is supposed to be 20–24 °C; the target is set to 22 °C.

Strategy 2: Priority given to battery cooling. The operating zone is supposed to be 20–32 °C; the target is set to 28 °C.

Strategy 3: Balanced control between passenger cabin cooling and battery cooling.

Simulations are carried out at ambient temperatures of 20 °C, 30 °C, and 40 °C. The initial passenger cabin temperature is set to 160% of the ambient temperature, accounting for the influence of solar radiation.

To enhance the rigor of the control strategy, the thermal management system is formulated within a model predictive control (MPC) framework, enabling coordinated regulation of battery temperature and cabin thermal comfort under

energy constraints. The control objective is defined through a multi-objective cost function:

$$J = w_b (T_b - T_{b,\text{ref}})^2 + w_c (T_c - T_{c,\text{ref}})^2 + w_e P_{\text{cool}}^2 \quad (2)$$

where: T_b and T_c denote the battery and cabin temperatures, respectively, $T_{b,\text{ref}}$ and $T_{c,\text{ref}}$ are their corresponding reference values, and P_{cool} represents the cooling power. The weighting factors w_b , w_c , w_e reflect the relative importance of battery thermal safety, passenger comfort, and energy efficiency. By adjusting these weighting factors, different control strategies can be realized: a cabin-priority strategy ($w_c \geq w_b$), a battery-priority strategy ($w_b \geq w_c$), and a balanced strategy ($w_b = w_c$). This formulation is consistent with MPC-based and multi-objective optimization approaches widely adopted in EV thermal management systems.

3. Results and Discussion

3.1. Thermal Performance Analysis

Simulation results obtained using the Amesim software indicate that, under control Strategy 1, the system prioritizes passenger cabin cooling. Specifically, the cabin temperature decreases rapidly and reaches a comfort threshold within approximately 70 s when the ambient temperature is 40 °C. However, this advantage is accompanied by a notable drawback, namely a relatively slow battery cooling rate. As a

consequence, the battery temperature remains elevated during the initial operating phase, as illustrated in Fig. 2. These results reveal an imbalance in the allocation of cooling energy, clearly reflecting the inherent trade-off between ensuring passenger thermal comfort and providing adequate thermal protection for the battery. Without appropriate adjustments to this control strategy, the battery temperature may exceed its optimal operating range, thereby adversely affecting battery performance and long-term durability. Under control Strategy 2, the system prioritizes cooling energy for the battery pack, resulting in a significantly faster battery cooling rate compared with Strategy 1. Consequently, the battery temperature is rapidly brought into the

optimal range, contributing to the preservation of battery performance and service life from the early stages of operation. However, this improvement comes at the expense of passenger cabin cooling performance. The cabin temperature decreases more slowly, causing occupants to experience the most severe phase of thermal discomfort during the initial period from approximately 100 to 300 s, as illustrated in Fig. 3. While this initial phase represents the most acute heat stress, the total duration required for the cabin to fully reach the target comfort threshold extends significantly longer, reaching 653.5 s at an ambient temperature of 40 °C, as quantified in Fig. 5. Such behavior may negatively impact passenger comfort, particularly under severe climatic conditions.

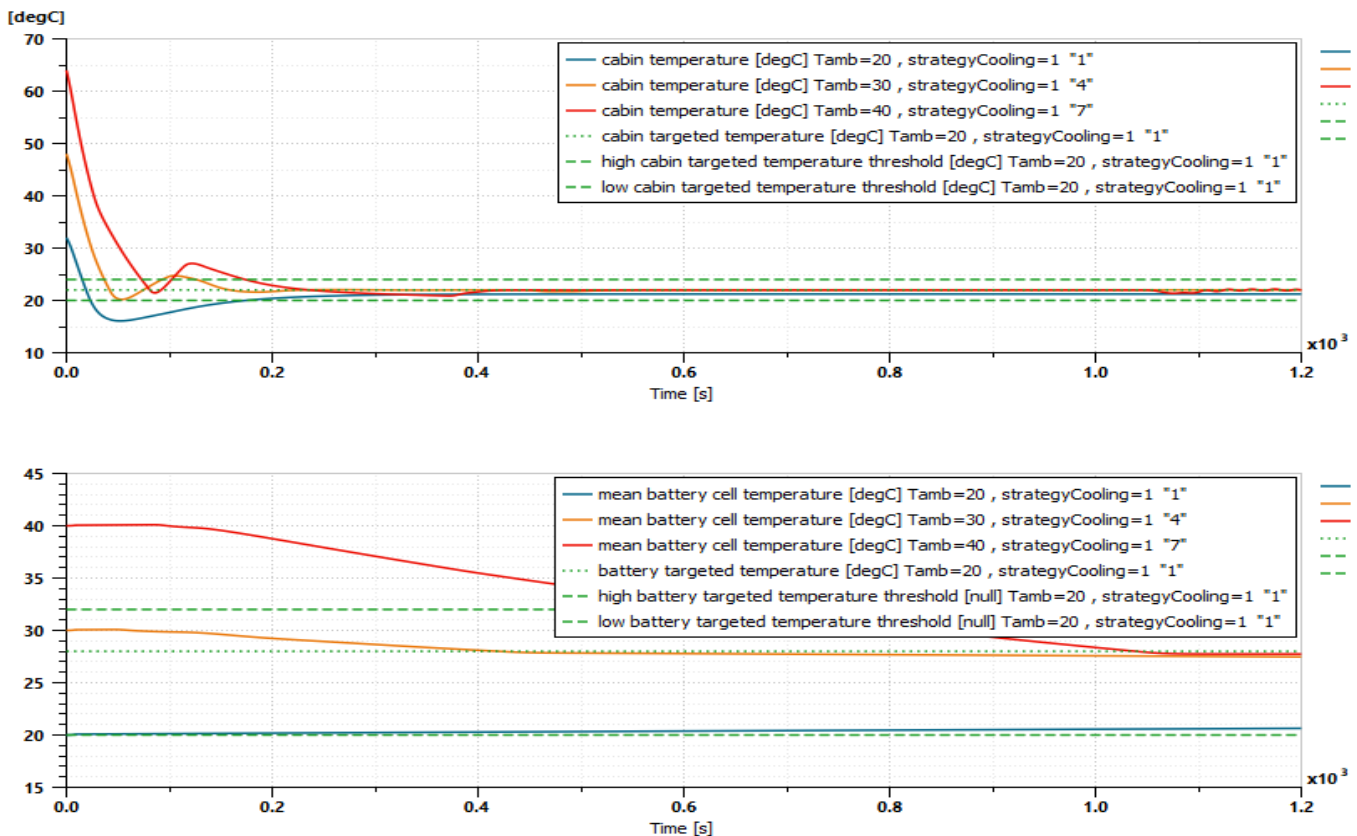


Fig. 2. Passenger cabin and battery temperature profiles under control Strategy 1

The results clearly demonstrate the trade-off inherent in thermal control objectives: when battery protection is prioritized, passenger thermal comfort is compromised. This strategy may therefore be more suitable for operating scenarios in which battery longevity is regarded as the primary objective, such as under high-load duty cycles or

extremely high ambient temperature conditions.

Under control Strategy 3, a more favorable balance between the two competing objectives, battery thermal protection and passenger comfort, is achieved. Specifically, the battery temperature is regulated at a level comparable to that obtained with control Strategy 2, indicating that battery

cooling remains effective and sufficiently rapid, as shown in Fig. 4. At the same time, the passenger cabin temperature is maintained within an acceptable range, avoiding the prolonged overheating observed under Strategy 2. Although

the cabin cooling rate is not as rapid as that achieved with control Strategy 1, the resulting temperature still satisfies thermal comfort criteria within a reasonable timeframe, thereby ensuring a comfortable operating environment for occupants.

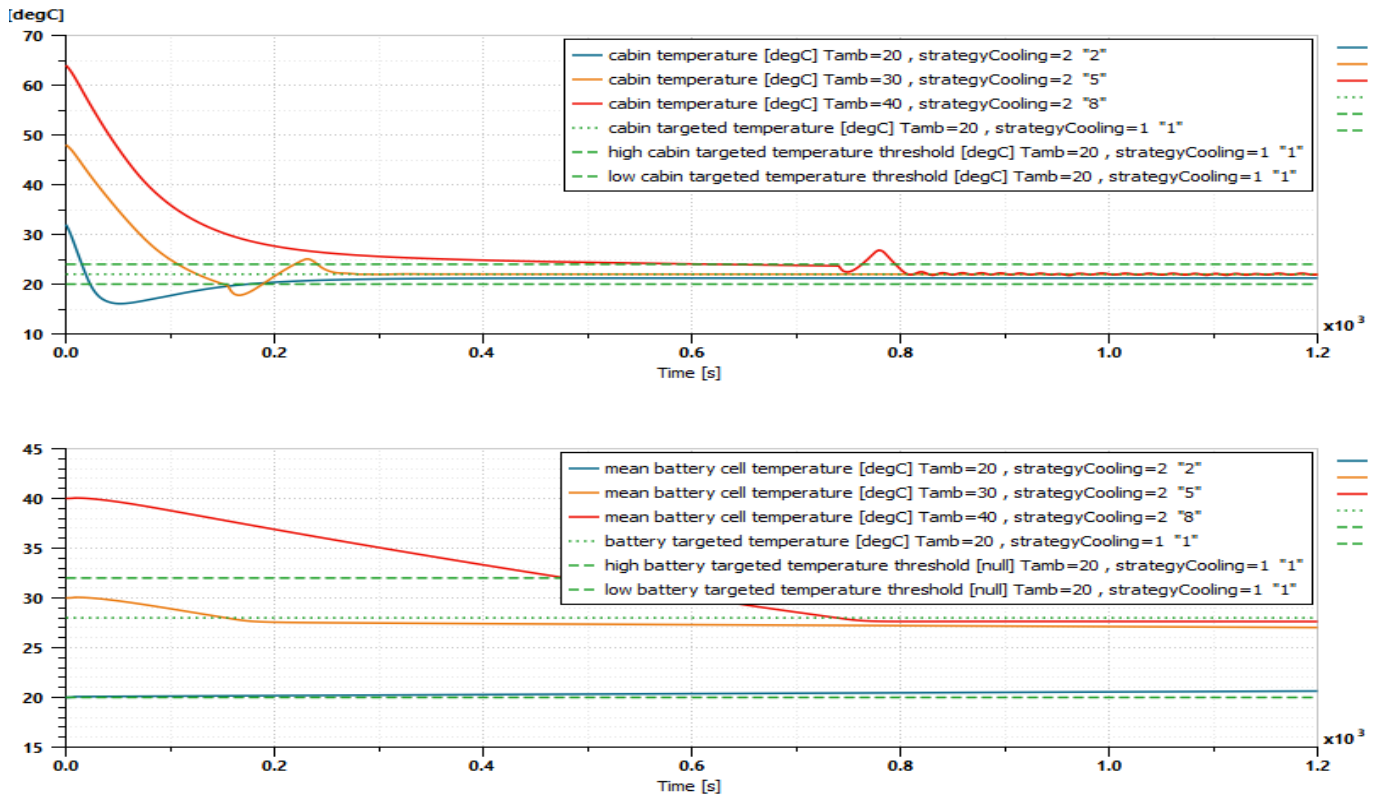


Fig. 3. Passenger cabin and battery temperature profiles under control Strategy 2

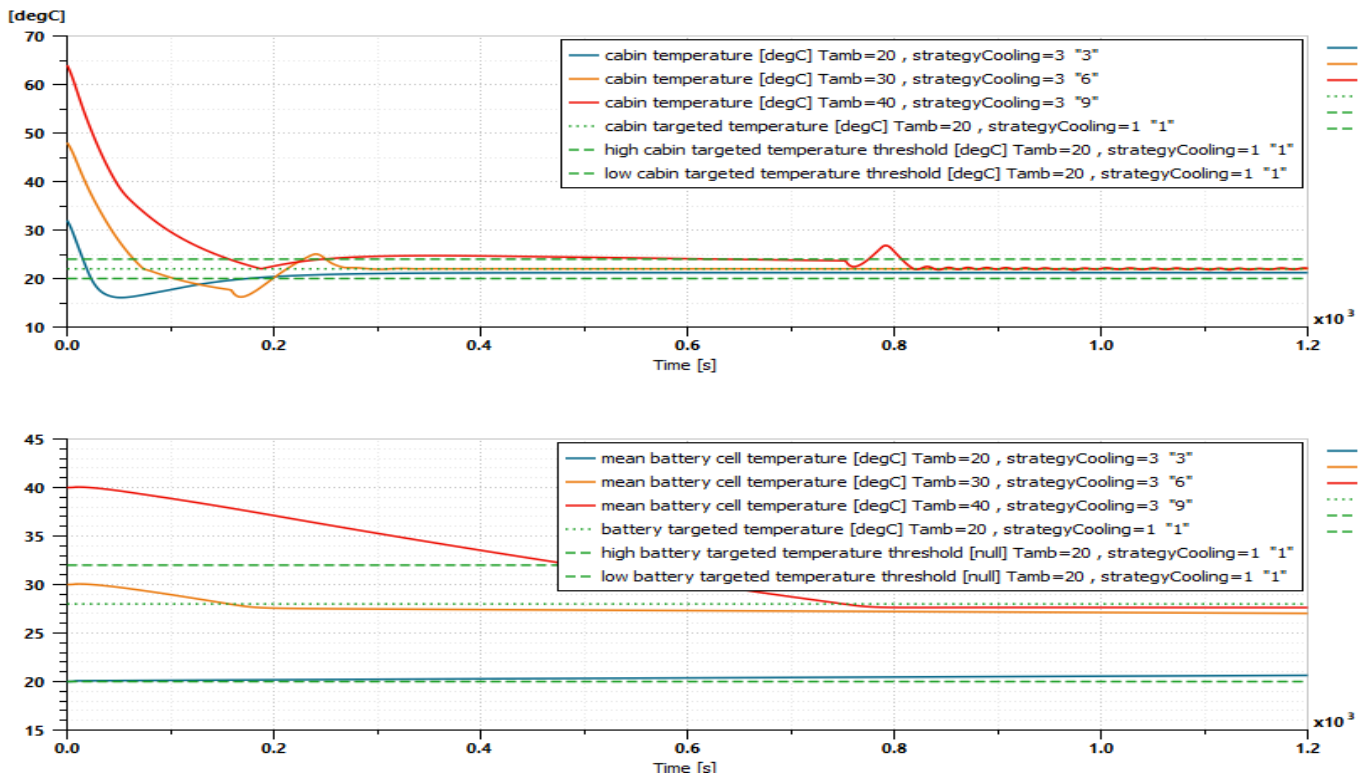


Fig. 4. Passenger cabin and battery temperature profiles under control Strategy 3

Based on the simulation results obtained by the authors, it can be observed that control Strategy 3 significantly enhances the cooling performance of the battery pack while simultaneously maintaining the passenger cabin cooling at an acceptable level. Indeed, the battery temperature achieved under this strategy is nearly equivalent to that obtained with control Strategy 2, whereas the cabin temperature remains at an intermediate level between those corresponding to control Strategy 1 and control Strategy 2.

Fig. 5 illustrates the total duration during which the passenger cabin remains in a thermally uncomfortable state at three ambient temperatures (20 °C, 30 °C, and 40 °C) under three different control strategies. The results indicate that, at a high ambient temperature (40 °C), control Strategy 1 provides the best passenger cabin comfort, exhibiting the shortest duration of cabin discomfort at 144.5 s, whereas control Strategy 2 results in the

highest level of passenger discomfort, with a duration of 653.5 s. Control Strategy 3, representing the combined approach, yields intermediate performance, with a duration of 572.5 s, demonstrating its capability to reconcile passenger cabin cooling effectiveness with other thermal requirements.

In summary, control Strategy 2 exhibits the highest effectiveness in cooling the battery pack, followed by control Strategy 3, while control Strategy 1 results in the longest battery cooling duration. Unlike strategies 1 and 2, which rely on fixed cooling priorities, Strategy 3 dynamically reallocates cooling capacity based on the instantaneous thermal demands of the battery and passenger cabin. As a result, it should not be interpreted as a simple average of two extreme strategies, but rather as a state-dependent compromise that inherently reflects multi-objective thermal management.

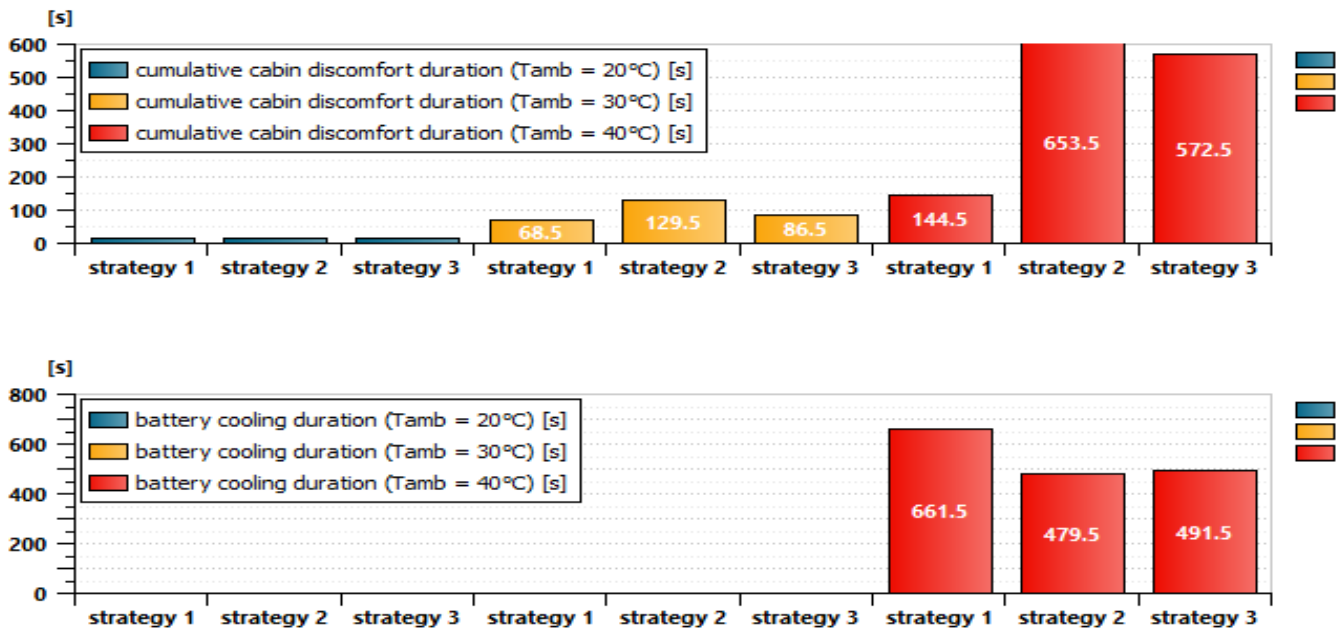


Fig. 5. Effects of ambient temperature and control strategy on passenger cabin discomfort duration and battery cooling time

3.2. Energy Consumption Analysis

The simulation results indicate that energy consumption tends to increase with ambient temperature, as the cooling demand for both the passenger cabin and the battery pack becomes more pronounced. As a consequence, the remaining charge of the HV battery at the end of

the driving cycle decreases as the ambient temperature rises. However, at a vehicle speed of 90 km/h, the simulation results show that the HV battery state exhibits no significant difference between ambient temperatures of 20 °C and 30 °C. This observation suggests that the influence of ambient temperature on energy consumption is not

strictly linear across the entire temperature range considered.

Energy consumption is evaluated using the state of charge (SOC) of the HV battery at the end of the driving cycle. At a speed of 90 km/h, the SOC

decreases as ambient temperature increases due to higher cooling loads, a trend that is more clearly illustrated in Fig. 6. Specifically, when the ambient temperature is 40 °C, the HV SOC for all three strategies is approximately 79.5%.

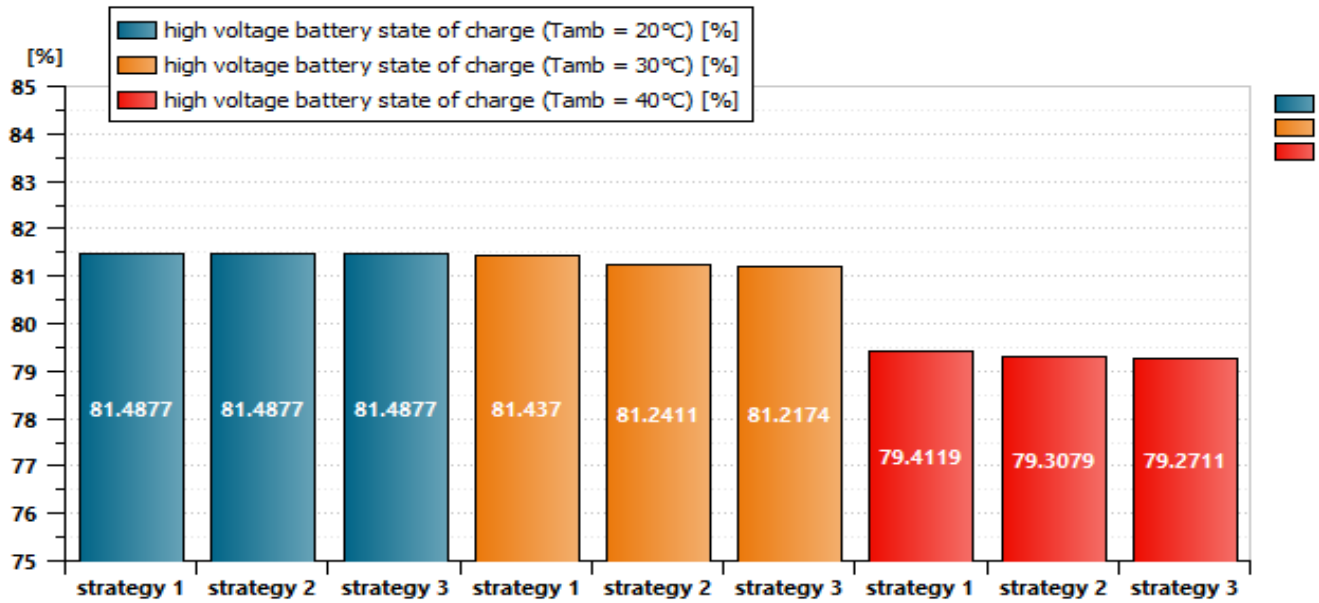


Fig. 6. Remaining state of charge of the high-voltage battery at a vehicle speed of 90 km/h

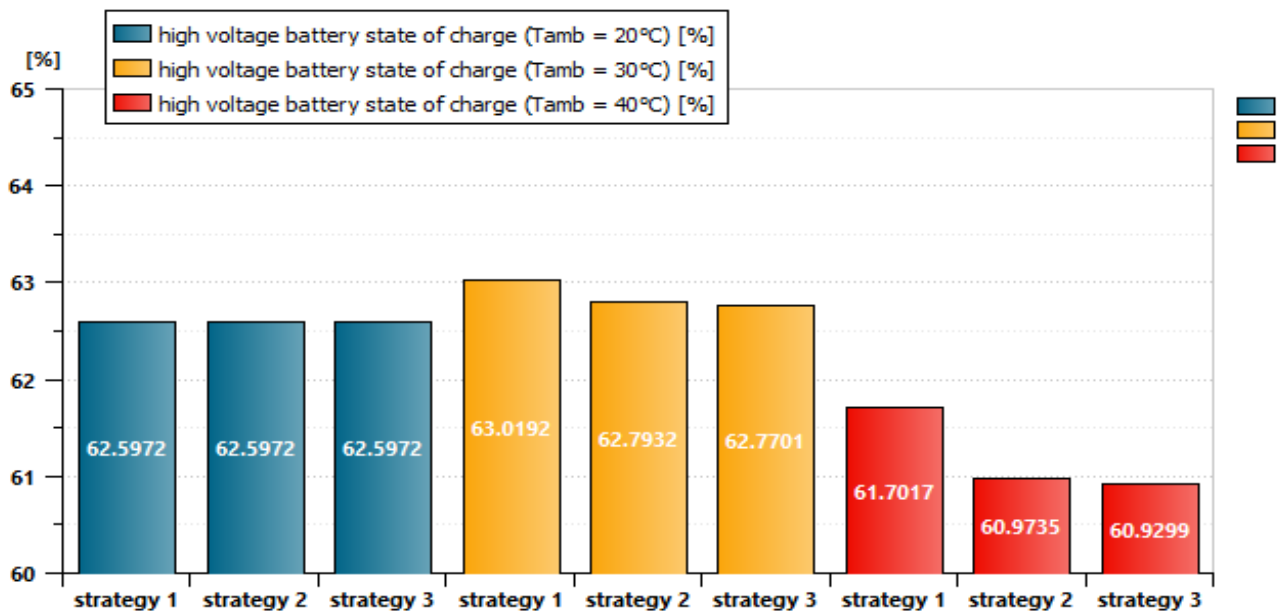


Fig. 7. Remaining state of charge of the high-voltage battery at a vehicle speed of 130 km/h

When the vehicle speed is increased from 90 km/h to 130 km/h, the total energy consumption of the system correspondingly increases, resulting in a lower remaining SOC of the HV battery after the driving cycle. Nevertheless, the simulation results reveal that, at this higher speed, the SOC of the HV battery at an ambient temperature of 20 °C is lower

than that observed at 30 °C. Specifically, for Strategy 1, Strategy 2, and Strategy 3, the SOC values are lower by 0.674%, 0.313%, and 0.276%, respectively. This phenomenon indicates that, at elevated vehicle speeds, the thermal and energy efficiency of the system may be influenced by ambient conditions in a more complex manner,

rather than strictly following a linear relationship between temperature and energy consumption, as illustrated in Fig. 7.

3.3. Physical Interpretation and System-Level Discussion

The aforementioned results may initially appear counterintuitive, as higher ambient temperatures are generally expected to require greater cooling energy. However, another important phenomenon that plays a significant role is the aerodynamic drag acting on the vehicle. At a given vehicle speed, the total energy consumption primarily consists of the energy required by the cooling loop, mainly through the chiller compressor, and the energy supplied to the electric traction motor for vehicle propulsion. The chiller operates predominantly during the initial phase of vehicle operation to cool the passenger cabin and the battery pack. After a certain period, as the temperatures of both the cabin and the battery decrease, the cooling demand is reduced, whereas the electric motor continues to consume energy continuously to maintain vehicle motion (Fig. 7).

The power consumption of the electric motor is directly related to the aerodynamic drag force acting on the vehicle. The aerodynamic drag force F_{aero} [N] is calculated as follows [15–16]:

$$F_{aero} = \frac{1}{2} \rho_{air} \cdot S \cdot C_z \cdot (v + v_{wind})^2 \quad (3)$$

where: ρ_{air} is the air density [kg/m³]; S is the vehicle frontal area exposed to airflow [m²]; C_z is the aerodynamic drag coefficient (dimensionless); v is the vehicle longitudinal speed [m/s]; v_{wind} is the headwind speed [m/s].

Air density is inversely proportional to temperature. Consequently, as ambient temperature increases, the power consumption of the electric traction motor decreases. Therefore, two opposing temperature-dependent effects coexist:

Higher ambient temperature leads to increased cooling power demand.

Higher ambient temperature results in reduced electric motor power consumption due to lower

aerodynamic drag.

This reasoning can also be applied to the vehicle speed of 90 km/h. The main difference lies in the magnitude of the aerodynamic drag force F_{aero} , which is significantly larger at 130 km/h than at 90 km/h due to the quadratic dependence on vehicle speed. As a result, at a speed of 130 km/h and for a given travel duration, the energy consumption associated with aerodynamic drag at 20 °C is substantially higher than that at 30 °C, rendering the energy consumed for cooling relatively negligible in comparison to the total energy demand. It should be noted that this conclusion is highly dependent on the driving duration. At a speed of 90 km/h, a similar conclusion may also be reached if the driving time is sufficiently extended.

3.4. Model validation and benchmarking against published studies

Due to the complexity of integrated vehicle thermal management systems, direct experimental validation at the full vehicle level is often limited by cost, instrumentation constraints, and proprietary data availability. Therefore, system-level thermal models are commonly validated through benchmarking against experimental and numerical studies reported in the literature, ensuring that simulated thermal responses remain consistent with established physical trends and realistic operating ranges, as summarized in Table 2.

The thermal modeling approach used in this work is consistent with a growing body of research where system-level BTMS models are benchmarked against experimental and high-fidelity studies. For example, thermal models of integrated vehicle thermal systems have been validated against real-world data, demonstrating good agreement between simulated and measured battery and cabin temperatures across a range of ambient conditions [17]. Similarly, literature reports on pack-level BTMS simulations show that effective cooling strategies can maintain temperatures within recommended operating ranges [18], and thermal models have been shown

to achieve temperature predictions within less than 1 °C error when compared against experimental measurements [19]. Together, these works provide confidence that the simulation results presented here reflect realistic thermal behaviour. In [20], the battery pack's thermal performance was assessed through both numerical and experimental approaches. The maximum temperature and temperature deviation were used as key BTMS performance metrics, with a maximum discrepancy of 3.12% between simulation and experimental results, indicating good agreement. The simulation

results in [21] were also validated against experimental data, demonstrating that an effective cooling strategy can maintain the battery temperature within the permissible range.

Although direct experimental validation is beyond the scope of this study, the consistency of the simulated thermal responses with experimentally validated and widely cited studies provides strong evidence that the proposed model captures the dominant physical mechanisms governing battery and cabin thermal behavior in electric vehicles.

Table 2. Benchmarking of thermal performance against published BTMS studies

Model type	Validation approach	Ambient temperature range	Battery temperature criterion	Key findings	Ref.
Integrated vehicle thermal model	Experimental validation	−20 to 40 °C	< 40 °C	Simulated cabin and battery temperatures closely matched vehicle test data	[17]
High-fidelity numerical simulation	Literature benchmark	25–45 °C	< 40–45 °C	Effective cooling maintains battery within recommended operating range	[18]
Pack-level thermal model	Experimental comparison	27–37 °C	< 40 °C	Temperature prediction error < 0.8 °C	[19]
Pack-level BTMS (air cooling)	Numerical + experimental benchmarking	~9–42 °C	Within recommended operating temperature range	Numerical results were consistent with experimental data (max error ~3.12 %)	[20]
CFD thermal model (OpenFOAM)	Comparison with literature and ANSYS results	~22–28 °C	< 22 °C	OpenFOAM simulation confirmed by comparison with literature & ANSYS benchmarks	[21]
System-level BTMS (Amesim)	Literature benchmarking	20–40 °C	< 40 °C	Cooling trends and temperature levels consistent with published studies	This study

4. Conclusions

This paper has developed and presented an

effective modeling framework to evaluate the impact of different cooling control strategies on

both passenger thermal comfort and battery temperature in electric vehicles. The proposed model employs a state-based control scheme to coordinate and optimize the cooling process, demonstrating that the combined control strategy provides a favorable compromise between battery cooling and passenger cabin conditioning. Specifically, battery cooling performance approaches the optimal level achieved when battery cooling is exclusively prioritized, while passenger cabin cooling is maintained at a reasonable level, thereby ensuring occupant comfort.

In addition, the model clearly captures the overall system behavior under various operating conditions as well as the total system energy consumption, highlighting the influence of multiple interacting physical phenomena on energy efficiency. Through these analyses, the study underscores the value of system-level simulation approaches in analyzing and optimizing electric vehicle operation.

Nevertheless, the present work is limited to cooling operation under the tested ambient conditions (20–40 °C), which primarily represent moderate-to-high thermal loads. This limitation will be addressed in future research by extending the model to include sub-zero start-up and warm-up operating modes. In subsequent studies, the electric vehicle model will be simulated over a wider range of ambient temperatures, particularly at low-temperature extremes (e.g., –15 °C to 0 °C), to provide a more comprehensive assessment of the effectiveness of cooling control strategies under diverse real-world operating conditions.

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Declaration of Generative AI

During the preparation of this work, the authors used ChatGPT in order to improve the readability and language of the manuscript. After

using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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