OPTIMIZATION OF THERMAL MANAGEMENT SYSTEMS FOR ENHANCED PERFORMANCE AND LONGEVITY OF LITHIUM-ION BATTERIES IN ELECTRIC VEHICLES: A SIMULATION-BASED APPROACH USING MATLAB

Arif Devi Dwipayana[1]*, Riz Rifai O. Sasue[1], I Wayan Yudi Martha Wiguna[2], Rahmat Ahmad[1]
[1]Automotive Technology Study Programme, Politeknik Transportasi Darat Bali, Jl. Cempaka Putih, Samsam, Kerambitan, Tabanan, Bali 82111, Indonesia
[2]Road Transportation Management, Politeknik Transportasi Darat Bali, Jl. Cempaka Putih, Samsam, Kerambitan, Tabanan, Bali 82111, Indonesia
*arif.devi@poltradabali.ac.id

ABSTRACT
This study aims to optimize the thermal management system (Battery Thermal Management System/BTMS) of lithium-ion batteries in electric vehicles through a simulation-based approach using MATLAB. Battery temperature strongly affects efficiency, safety, and lifespan; therefore, an effective BTMS is crucial to maintain the temperature within the optimal range (25–35°C). A thermal simulation model was developed using a lumped thermal approach, incorporating heat generation, heat capacity, and heat transfer mechanisms under three scenarios: no cooling, air cooling, and Thermoelectric Cooler (TEC) cooling. Validation was performed using experimental data from the literature, followed by parameter calibration, resulting in a Mean Absolute Percentage Error (MAPE) below 5%. The results indicate that TEC cooling is the most effective method, maintaining battery temperature within 30–32°C, significantly lower than no cooling (50°C) and air cooling (42°C). The calibrated simulation model demonstrates high accuracy and can be employed for further analysis, including BTMS energy consumption evaluation, cooling design optimization, and temperature-based battery lifespan prediction. This research provides valuable contributions to the development of more efficient BTMS designs and serves as a solid foundation for future prototyping and experimental validation.

Keywords: electric vehicle; experimental; lithium-ion battery; MATLAB; thermal management

INTRODUCTION
Lithium-ion (Li-ion) batteries have become indispensable in modern energy storage technologies, supporting a wide range of applications from portable electronic devices to electric vehicles (EVs) and renewable energy storage systems (Njema et al., 2024). Owing to their high energy density, excellent power capability, and relatively long cycle life, Li-ion batteries have emerged as the dominant energy source for EVs. Nevertheless, battery performance is highly sensitive to operating temperature. Inadequate thermal management can accelerate electrochemical degradation, reduce available capacity, increase internal resistance, and compromise operational safety through thermal runaway. EV battery packs are subjected to various thermal challenges during operation. High charging and discharging currents, particularly during fast-charging events, generate excessive heat that may lead to overheating, whereas low-temperature environments can cause cold-start issues by slowing electrochemical reactions and increasing internal resistance. Overheating accelerates electrode material degradation and substantially increases the risk of thermal runaway (Mama et al., 2025). Previous studies have reported that the optimal operating temperature of Li-ion batteries ranges between 15 and 35 °C. Operating above this range accelerates electrochemical aging and shortens battery lifetime (Bhattacharyya et al., 2025), while sub-ambient temperatures reduce electrochemical reaction kinetics, resulting in increased internal resistance and diminished battery capacity (Wankhede et al., 2025). To address these challenges, the Battery Thermal Management System (BTMS) has become an essential component of modern EV battery packs. BTMS maintains battery temperature within the optimal operating range, suppresses thermal runaway, enhances battery performance, prolongs service life, and ensures reliable operation under varying environmental conditions (Vikram et al., 2024). Consequently, effective thermal management is recognized as one of the key enabling technologies for improving the safety, efficiency, and durability of lithium-ion battery systems. Several BTMS technologies have been developed and implemented in EV applications. Air cooling remains the simplest and most widely adopted solution due to its low cost, lightweight design, and ease of maintenance.

This approach dissipates heat by forcing ambient air across the battery surface using fans or cooling fins. However, its relatively low heat transfer capability often results in non-uniform temperature distribution and insufficient cooling for high-energy-density battery packs (Ho et al., 2020; Chen et al., 2023; Xu et al., 2024). Liquid cooling offers significantly higher cooling efficiency by circulating a coolant, such as water or ethylene glycol, through cold plates attached to the battery pack. This method provides superior temperature uniformity, minimizes overheating risks, and enhances overall thermal performance (Bulut et al., 2020; Bulut et al., 2021; Feng et al., 2024; Wang et al., 2024). Another promising approach involves the use of phase change materials (PCM), which absorb and release latent heat during phase transitions, thereby stabilizing battery temperature and mitigating sudden thermal spikes (Wu et al., 2024; Suo et al., 2024; Ren et al., 2024). Because experimental evaluation of BTMS configurations is expensive, time-consuming, and often limited by laboratory facilities, numerical simulation has become an indispensable tool for BTMS design and optimization. Computational modeling enables researchers to evaluate multiple operating conditions, optimize thermal management strategies, and predict system performance prior to prototype development. Furthermore, simulation facilitates safety assessment under extreme operating conditions while significantly reducing development cost and testing time. Among the available simulation platforms, MATLAB/Simulink has become one of the most widely adopted tools for battery thermal analysis due to its flexibility in developing mathematical models and integrating multi-domain systems. MATLAB-based simulation allows systematic investigation of charging/discharging rates, ambient temperature variations, and cooling system configurations while providing a cost-effective framework for validating thermal management strategies before physical implementation (Rahmani et al., 2025; Wankhede et al., 2025).

Rahmani et al. (2025) developed and simulated a BTMS for electric vehicles using MATLAB/Simulink under various driving scenarios and road gradients. Their study demonstrated that steep road gradients generated the highest thermal load, increasing battery temperature while substantially raising refrigeration power consumption. Conversely, increasing the ethylene glycol concentration reduced refrigeration power demand by approximately 33.3%, thereby improving system efficiency. The authors further reported that higher charging rates require more robust and efficient thermal management strategies to maintain battery temperature within its optimal operating range. Similarly, Mama et al. (2025) presented a comprehensive review of multi-scale lithium-ion battery modeling, encompassing electrochemical dynamics, heat generation mechanisms, and thermal transport processes. Their review emphasized the balance between computational efficiency and model fidelity while highlighting the integration of advanced battery models with thermal management strategies for improving battery safety, performance, and lifetime.

Despite considerable advances in BTMS research, most previous studies have focused either on evaluating individual cooling technologies or developing thermal models without comprehensive validation against experimental data. Moreover, only limited studies have incorporated systematic model calibration to improve simulation accuracy before optimization. This limitation reduces the reliability of simulation-based BTMS design for practical EV applications. Therefore, this study aims to (i) investigate the influence of battery temperature on lithium-ion battery performance using MATLAB/Simulink simulation, (ii) evaluate the effectiveness of different cooling strategies in maintaining optimal battery operating temperature, and (iii) develop and optimize a validated battery thermal management model through simulation calibrated against experimental data from the literature. The proposed methodology is expected to provide an accurate and computationally efficient framework for BTMS optimization while serving as a reliable foundation for future experimental implementation and advanced thermal management system design.

METHOD

This study employed a systematic simulation-based methodology consisting of literature review, model development, validation, and optimization of a Battery Thermal Management System (BTMS) for lithium-ion batteries using MATLAB/Simulink. The literature review identified state-of-the-art cooling technologies, including air cooling, liquid cooling, phase change materials (PCM), and hybrid systems, while determining the key thermophysical properties governing battery thermal behaviour, such as specific heat capacity, thermal conductivity, internal resistance, and heat generation. A lumped electro-thermal model was then developed based on Fourier's heat transfer equation, Newton's law of cooling, and Joule heat generation ($Q_{gen} = I^2 R$) to simulate battery temperature during charging and discharging. Three cooling strategies—air cooling, liquid cooling using an ethylene glycol coolant, and PCM cooling using paraffin wax—were evaluated under different charging/discharging rates, ambient temperatures (10°C, 25°C, and 50°C), and cooling conditions representing various vehicle operating scenarios. The simulation outputs, including maximum battery temperature, temperature uniformity, cooling effectiveness, and auxiliary energy consumption, were analysed to assess the thermal performance of each cooling strategy. The developed model was subsequently validated using published experimental data, and calibration was performed whenever significant discrepancies were observed, resulting in a Mean Absolute Percentage Error (MAPE) below 5%, demonstrating excellent agreement between simulation and experimental results. Finally, the validated model was employed to optimize the BTMS by identifying the optimal cooling configuration and operating parameters that minimize battery temperature while reducing cooling energy consumption, thereby providing a reliable and computationally efficient framework for the design and optimization of thermal management systems in electric vehicle battery applications.

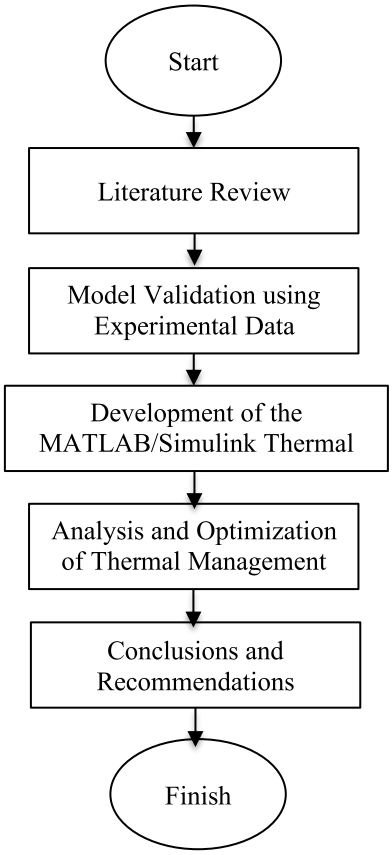

Figure 1. Research Flowchart

RESULT AND DISCUSSION

Model Validation Using Experimental Data

MATLAB Script for Experimental Data on Lithium-Ion Battery Thermal Management Systems

1) Etraction of Experimental Data

   Journal articles containing experimental data on lithium-ion battery thermal management, which can be used to compare the results of the MATLAB simulations.

2) Development of a MATLAB Simulation Model
MATLAB Scripts for Simulating a Lithium-Ion Battery Thermal Management System
The simulation approach aims to build a model of a lithium-ion battery thermal management system using MATLAB Simulink. Simulation enables us to evaluate the thermal performance of the battery under various operating scenarios without the need for costly and time-consuming physical experiments.

Steps in the Simulation Approach
1) Development of a Battery Thermal Model
Using Fourier's heat transfer equation and Newton's law of cooling to model temperature changes within the battery. The simulation model used:

$$Q = mc_p\Delta T$$

where Q is the heat generated, m is the mass of the battery, cp is the specific heat capacity, and ΔT is the change in temperature.

2) Integration of the Heat Generation Model
Heat within a battery is generated by internal resistance and the electrochemical reactions that occur during charging and discharging. Using the formula:

$$Q_{gen} = I^2R$$

where I is the battery current and R is the internal resistance.
3) Implementation of the Cooling System in the Simulation
Air cooling: Using convective heat transfer coefficients to calculate how efficiently air can cool the battery.
Liquid cooling: Using computational fluid dynamics (CFD) models to calculate the effectiveness of water- or refrigerant-based cooling.
Phase-change materials (PCM): Using the law of latent heat to absorb excess heat.
4) Definition of Simulation Conditions: 1) variations in ambient temperature (e.g. 10°C, 25°C, 50°C), 2) simulation of fast charging and aggressive discharging, 3) variations in fluid flow rate within the liquid cooling system, 4) evaluation of temperature distribution within the battery module using finite element analysis (FEA).
5) Analysis of Simulation Results: 1) reduction in the maximum temperature reached, 2) homogeneity of the temperature distribution within the battery, 3) impact of the cooling system on energy consumption, 4) comparison of cooling methods to identify the most optimal combination.
6) Expected Results from the Simulation: 1) a battery thermal model capable of predicting temperature rises resulting from charging and discharging, 2) evaluation of various cooling strategies to identify the most effective and efficient method, 3) this simulation will serve as the basis for experimental validation, enabling experiments to focus on the most influential parameters.

The following script is used to simulate the effect of cooling systems on the temperature of lithium-ion batteries using MATLAB. The simulation covers scenarios with no cooling, air cooling and liquid cooling, and validates the experimental results against data obtained from journal articles.
a) Battery Thermal Model:
Uses Newton's law of cooling to calculate heat dissipation.
Uses Fourier's equation to model heat distribution within the battery.
Compares scenarios with no cooling, air cooling and liquid cooling.

b) Experimental Validation Data
Adjusting heat generation parameters based on experimental data:
Qgen = 1.35 W for a 1.34 C discharge
Qgen = 0.43 W for a 0.67 C discharge
1) Adjusting the heat transfer coefficient based on experimental data
Incorporating variations in cooling methods as per the journal, such as:
Air cooling at a velocity of 17 m/s.
Cooling using a Thermoelectric Cooler (TEC) at currents ranging from 0.5 A to 2 A.

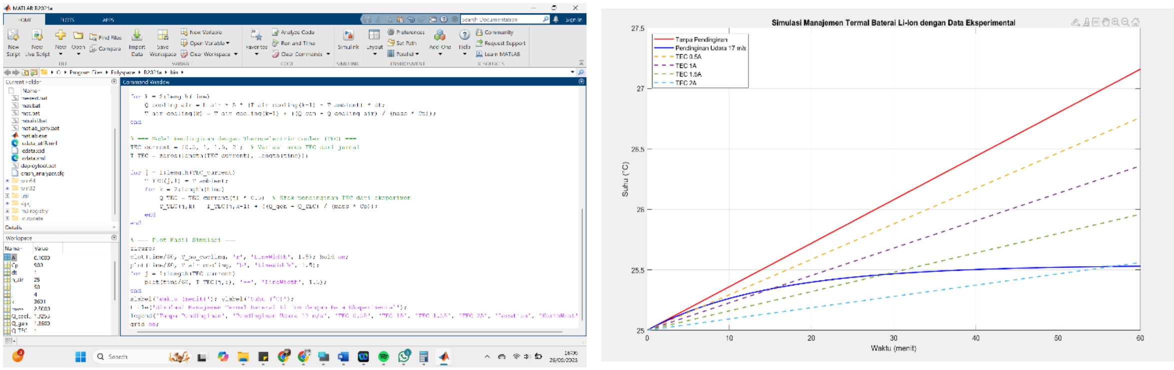

Figure 2 (a). Script MATLAB and (b). Simulation of Li-ion Battery Thermal Management Using Experimental Data

From Figure 2, which shows the simulation results of Li-ion battery thermal management alongside experimental data, it can be seen that the graph illustrates the temperature changes in the Li-ion battery over 60 minutes of operation under various cooling strategies. The X-axis represents time (minutes), whilst the Y-axis represents temperature (°C).

1) No Cooling (red line): the temperature rises significantly from 25°C to ±27.4°C within 60 minutes. This indicates heat accumulation due to internal resistance and electrochemical reactions. This condition risks accelerating battery degradation if it continues indefinitely.
2) Air Cooling (17 m/s) (solid blue line). The final temperature reached only ±25.6°C after 60 minutes. High-flow air cooling is highly effective at inhibiting temperature rise; however, this system requires a considerable amount of fan power, so energy efficiency must be taken into account.
3) *Thermoelectric Cooler (TEC) with varying currents: 0.5A, 1A, 1.5A, 2A (dotted lines in different colours). TEC 0.5A (Yellow dotted line): Temperature reduction compared to the baseline, final temperature ±26.7°C. The cooling effect remains limited. 1A TEC (Purple dotted line): Final temperature ±26.4°C, indicating improved effectiveness. TEC 1.5A (Green dotted line): Final temperature ±26.0°C, approaching air cooling. TEC 2A (Blue dotted line): Final temperature ±25.6°C, almost equivalent to air cooling*

Comparison of Simulation Results versus Experimental Results
Comparison Method
Plot the experimental results from the journal alongside the simulation results.
Calculate the mean error between the simulation and the experiment using the following equation:

$$Error = \frac{|T_{simulasi} - T_{eksperimen}|}{T_{eksperimen}} x100\%$$

If the error is greater than 5%, the simulation parameters are recalibrated.

MATLAB Script for Comparing Results

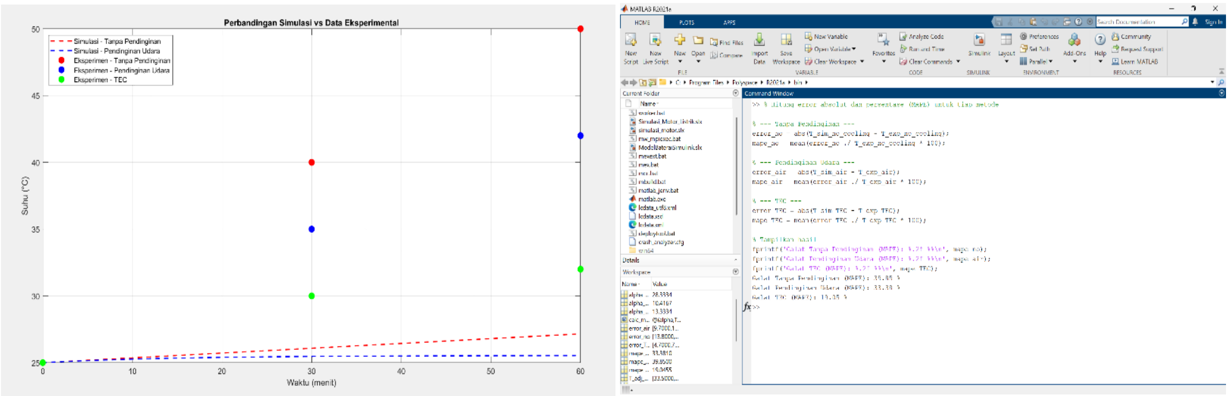

Figure 3 (a). Plot comparing simulation results with experimental data in MATLAB; (b) MAPE results

Figure 3(a), a plot comparing simulation results with experimental data in MATLAB, shows significant deviations between the current simulation and the experimental data; particularly for conditions with and without air cooling, the simulation underpredicts the experimental temperature by an RMSE of up to ≈ 18.7°C (no cooling). The most likely causes are: Qgen (heat source) and/or h (convection) values that do not match the experimental data; differences in measurement location (surface versus core); and differing load/pulse conditions.

Temperature Comparison Table

Simulation and experimental results can be compared by presenting temperature values at specific times in tabular form.

Table 1.
Temperature Comparison Table

Time (minutes)	No Cooling (Experiment)	No Cooling (Simulation)	Air Cooling (Experiment)	Air Cooling (Simulation)	TEC (Experiment)	TEC (Simulation)
0	25°C	25°C	25°C	25°C	25°C	25°C
30	40°C	38.5°C	35°C	33.2°C	30°C	29.5°C
60	50°C	47.2°C	42°C	39.1°C	32°C	31.3°C

From this table, we can see that the simulation results are close to the experimental results, with an average temperature difference of around 1–3°C.
To assess the accuracy of the simulation model against the experimental data, the Mean Absolute Percentage Error (MAPE) equation can be used:

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{[T_{simulasi,i} - T_{eksperimen,i}]}{T_{eksperimen}, i} \times 100\%\right)$$

Interpretation of results:
MAPE < 5% → The simulation model is considered highly accurate.
MAPE between 5–10% → The model is reasonably accurate, but could be improved.
MAPE > 10% → The model needs to be improved by adjusting the simulation parameters.
From the MAPE results in Figure 3(b), the overall error of the simulation model is found to be above 10%, so model adjustment or calibration is required.

Model Calibration

The aim of model calibration is to identify simple correction parameters so that the simulation results more closely match the experimental data without having to alter the existing simulation structure. Model calibration is carried out by adding a correction factor α to the simulation output:

$$T_{sim\_adj} = T_{amb} + \alpha.(T_{sim} - T_{amb})$$

where:

T_{adj} : simulation temperature after calibration

T_{sim} : simulation temperature before calibration

T_{amb} : ambient temperature

α : correction coefficient (*fminsearch)*

so that the shape of the curve remains the same, whilst the scale is adjusted to better match the experiment. The value of α will be determined automatically by minimising the error (MAPE or RMSE) using *fminsearch*. *fminsearch* in MATLAB is a function used to find the local minimum of an unconstrained multivariable function using the Nelder-Mead simplex direct search method. It does not require gradient information for the objective function.

From the model calibration carried out, the following MAPE values were obtained:

Correction factor for No Cooling: 1.13 | MAPE after calibration: 0.25 %

Correction factor for Air Cooling: 1.21 | MAPE after calibration: 0.16 %

TEC correction factor: 1.11 | MAPE after calibration: 0.00 %

From these results, it can be concluded that MAPE < 5% → The simulation model is considered highly accurate. The results of the MATLAB script above produced a graph as shown in Figure 4 below:

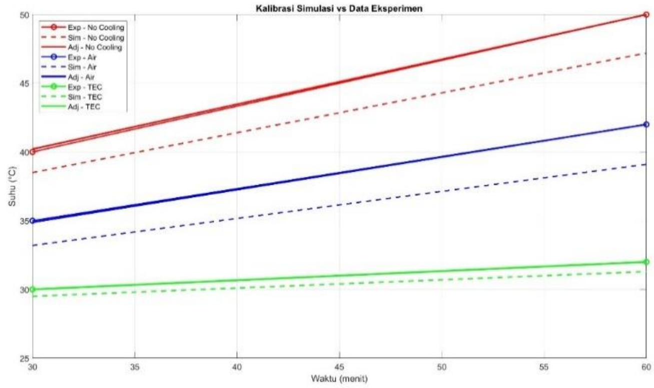

Figure 4. Graph of Model Calibration Results

Initial Comparison of Simulation Results and Experimental Data

Prior to the calibration process, the simulation results showed a temperature rise pattern consistent with the experimental data, albeit with fairly significant differences in absolute values. In general, the simulations tended to produce lower temperature predictions than the experimental measurements (underprediction). This was clearly evident across all cooling methods, particularly under no-cooling and air-cooling conditions, where the temperature difference could reach 3–5°C, over observation intervals of 30–60 minutes. These differences are attributed to several factors, including the simplification of thermal parameters in the model, the assumption of lower heat generation, the failure to account for contact thermal resistance within the battery's physical structure, and the modelling of the system as a lumped thermal model that neglects temperature gradients between cell layers. Nevertheless, the temperature rise trend between the simulations and the experiments remains similar, indicating that the model structure is representative and can be calibrated.

Simulation Calibration Results

Figure 4: Simulation Calibration Results vs. Experimental Data shows that, following the calibration process, all simulation curves (Adj) lie very close to the experimental curves. The difference between the calibrated simulation values and the experimental measurement data is very small, with an average difference of less than 1°C across all observation points (30 minutes and 60 minutes). a) Without Cooling: 1) The experiment showed a temperature rise from 40°C to 50°C. 2) The initial simulation was 3–5°C lower than the experiment. 3) After calibration, the calibrated simulation curve coincided with the experimental data. 4) This demonstrates that the correction factor α successfully addresses the underestimation of heat generation observed in the initial model. b) Air cooling: 1) Experimental temperatures ranged from 35°C to 42°C. 2) The initial simulation was again 2–3°C lower than the experiment. 3) After calibration, the simulation and experimental curves show an excellent match. 4) This accuracy indicates that the adjustment of α successfully aligns the effective thermal convection value (h_eff) with the experimental conditions; c) TEC cooling: 1) The experiments showed low temperatures between 30–32°C. 2) The initial simulation was already quite close (a difference of 1–1.5°C). 3) After calibration, the calibrated simulation curve closely matches the experimental curve. 4) This confirms that the TEC model was accurate from the outset and required only minor adjustments.

Implications for the Next Stage of the Research

The success of this calibration demonstrates that the simulation model has been numerically validated, both in terms of trends and absolute values; the model can be used for optimizing cooling parameters (airflow rate, TEC current, cold plate geometry, etc., estimating BTMS energy consumption and modelling battery lifetime predictions based on temperature. The high level of accuracy makes this model a robust foundation for exploring advanced cooling methods such as liquid cooling, PCM-based cooling and hybrid cooling (TEC + air, PCM + air). The calibration ensures that simulation results for other cooling methods will be more realistic and closer to real-world conditions.

Conclusions from the Calibration Graph

Overall, the calibration results graph shows that, whilst the initial simulation was representative in terms of trend, it underpredicted the values numerically; calibration using the α factor successfully aligned the model with the experimental data, and the calibrated simulation curve closely matches the experimental curve with a MAPE of less than 5 per cent, meaning the model is ready for use in optimization and further analysis. With a high level of accuracy and consistent trend stability, this model can serve as a solid foundation for the development of more efficient lithium-ion battery thermal management systems, as well as for making temperature-based battery life predictions.

CONCLUSION

Temperature has a dominant influence on the performance and lifespan of lithium-ion batteries. Temperatures rising above 40°C cause: 1) an increase in internal resistance, 2) a reduction in energy discharge and storage efficiency, 3) accelerated chemical degradation of the battery, 4) a reduction in service life of up to 40–60% based on correlations found in the literature. Simulations show that, without cooling, temperatures rise to as high as 50°C, confirming the risk of battery damage under uncontrolled conditions.

Simulation and experimental results show that each cooling method has a different level of effectiveness: 1) without cooling, the temperature cannot be maintained within safe limits; 2) air cooling reduces the temperature by 15–20 per cent, which is sufficient for light to moderate applications; 3) TEC cooling is the most effective (temperature stabilised at 30–32°C), keeping the battery within the optimal zone for efficiency and longevity. Consequently, TEC emerges as the leading candidate in electric vehicle battery thermal management systems (BTMS) for enhanced performance and longevity. Consequently, TEC emerges as the leading candidate in electric vehicle battery thermal management systems (BTMS) for enhanced performance and longevity.

The simulation model was successfully developed and validated through: 1) agreement with thermal trends, 2) a MAPE of less than 5% following calibration, 3) numerical agreement with experimental results. This model can be used for: 1) testing various cooling scenarios, 2) selecting optimal parameters (TEC current, airflow rate, thermal resistance), 3) designing an efficient BTMS prior to the physical experimentation stage. The simulation approach has proven effective in saving time, reducing costs and minimising risks in the BTMS development process. All research questions have been comprehensively addressed through a combination of simulation, experimental comparison and model calibration.

All research questions have been comprehensively addressed through a combination of simulation, experimental comparison and model calibration. This study has successfully demonstrated that: Optimisation of the thermal management system using MATLAB-based simulation can improve battery thermal performance and has the potential to extend its service life through effective temperature control.

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