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Simulation and Performance Analysis of Thermal Battery Management System Using MATLAB

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ABSTRACT

The increasing use of lithium-ion batteries in electric vehicles, renewable energy storage systems, and portable electronic devices has created a strong demand for efficient Thermal Battery Management Systems (TBMS). Battery temperature is one key parameter affecting its safety, efficiency and thermal stability as well operational life. This leads directly to thermal runaway, and extreme heating when charging and discharging that can limit performance and increase battery ageing. This study used MATLAB for simulating the thermal behaviour of a battery pack under various cooling conditions. The cooling scenarios simulated (tagged in circles) were no cooling (black), air-cooling (blue) and liquid cooling (red). MATLAB coding for battery heat generation and thermal equations (Lumped Thermal Model) The values of most important parameters used in simulation are given in the Table 1, which include thermal capacity, ambient temperature, battery current etc.. The battery is simulated without cooling, the temperature of 77.42 °C and this is already a very dangerous overheating state. Comparing above performances with moderate ones gave us an average of battery cooled by air: about 34.37 °C; The most exceptional thermal performance pertained to liquid cooling itself as this also eased more thermally analogous low battery temperature (approximately 28.12 °C) than its others and it possessed a better stability compared to heat loss capability idea of lower lab temperatures indicated any rigorous thermal stability comparison among all above discussed phenomena [30]. This simulation thus provided evidence of thermal management system as an essential component of battery safety, reliability and longevity for electric vehicle propulsion.

Keywords: *Thermal Battery Management System, Lithium-Ion Battery, MATLAB Simulation, Liquid Cooling, Thermal Runaway.*

I. Introduction

The rapid growth of electric vehicles (EVs), renewable energy storage systems, and portable electronic devices has significantly increased the importance of lithium-ion batteries in modern energy applications. They have a very wide application, which is why lithium-ion batteries are the most widely used due to their high energy density, long cycle life, low self-discharge rate and good performance in all operational states. Nonetheless, the performance, security as well as life time of batteries is extremely dependent on operative temperature. Overheating in charging and discharging process can cause thermal runaway, thermal imbalance, efficiency reduction, degradation acceleration and extreme safety hazards. Thus, the Thermal Battery Management System (TBMS) should be developed to further guarantee battery reliability and safety during the operating temperature range of the batteries (Lin et al., 2021; Rao et al., 2025).

This implies that conventional cooling is frequently ineffective in the case of scattered heat and uneven temperatures, such as those seen in sophisticated battery packs. This is followed by thermal management systems featuring active, passive and hybrid types that the scientist have studied to figure out how they can enhance heat dissipation for energy efficient. In a study of recent Asadi-Ghajarlu (2026), a design resulted from converting leaf structures, represented an innovative scheme for heating or cooling plates with the purpose of refining fluid distribution to the channels and reducing pressure loss. In a different study, Chen (2026) proposed a novel thermal management system that may not only cool the battery effectively but also ameliorate the energy consumption by integrating both phase change materials and heat pipes with thermoelectric modules. Blind (2026) incorporated a vapor chamber and thermoelectric-assisted liquid cooling system that was able to dissipate heat at very quick rates with low energy loss. In addition, new air conditioning optimization methods and intelligent control strategies are increasingly integrated on thermal management systems. Cheng et al. The study (2024) investigated BTMS optimization with deep reinforcement learning while the impact of AI, digital twin technologies and smart materials on next-gen battery thermal management was reviewed in (2025). These advancements offer further justification when arguing that thermal management systems should assist not only the safety and thermal stability of batteries but also their energy efficiency enhancement or even environmental sustainability attributes, so one can have more effective designs in applications like electric vehicles or large-scale energy storage.

II. Review Study and Findings

Authors & Year	Study Focus	Method / Approach	Key Findings	Conclusion
Asadi-Ghajarlu et al. (2026)	Bio-inspired and hybrid thermal management system for lithium-ion batteries	Developed biomimetic cold-plate design based on leaf vascular networks with embedded heat pipe integration	Reduced pressure drop, improved temperature uniformity, minimized hot spots, and achieved efficient cooling at lower coolant flow rates	Bio-inspired hybrid cooling systems improved battery life, reduced pumping energy, and supported lightweight EV thermal management

Chen et al. (2026)	Hybrid BTMS integrating PCM, heat pipes, and thermoelectric modules	Developed multiphysics numerical model with dynamic thermoelectric operation strategy	Achieved self-powered ratio (SPR) of 2.65%, optimized coolant flow and PCM properties, and reduced energy consumption	Multifunctional low-energy BTMS provided improved thermal safety and energy efficiency
Luo et al. (2026)	Hybrid BTMS using vapor chambers, TECs, and liquid cooling	Developed thermo-electro-fluid multiphysics model and optimized operating conditions	Reduced battery temperature below 313.15 K within 221 s, maintained temperature uniformity within 5 K, and reduced energy consumption by over 80%	Hybrid cooling strategy balanced rapid cooling performance and energy conservation
Boretti et al. (2025)	Review of advanced BTMS technologies	Systematic review of active, passive, and hybrid cooling methods	Highlighted graphene-reinforced PCMs, microchannel cooling, digital twin-assisted control, and AI-based thermal management	Emerging intelligent and hybrid technologies could improve battery sustainability, reliability, and scalability
Rao et al. (2025)	Review of lithium-ion battery safety and thermal management	Comprehensive review of thermal runaway, battery health monitoring, and safety systems	Identified thermal runaway causes and emphasized thermal management and battery management systems	Effective BTMS and health management systems were essential for safe battery operation
Tawiah et al. (2025)	Carbon-based materials in battery thermal management	Review of graphite, graphene, carbon nanotubes, carbon foams, and aerogels	Carbon-based materials enhanced heat dissipation and supported hybrid BTMS development	Intelligent and sustainable carbon-based thermal materials showed strong future potential
Paneerselvam et al. (2024)	Thermal management techniques for EV batteries	Review of active, passive, and hybrid cooling systems	Hybrid BTMS combined advantages of active and passive methods and improved thermal stability	Efficient BTMS enhanced battery life and EV performance

Gonzalez-Agirre et al. (2024)	Dielectric flow and tab-cooling thermal management system	Developed and experimentally validated dielectric flow cooling prototype	Reduced operating temperatures, minimized thermal gradients, and achieved low pumping energy consumption	Dielectric tab-cooling systems showed strong potential for EV battery applications
Cheng et al. (2024)	Deep reinforcement learning-based battery thermal optimization	Applied DRL optimization to PCM-water channel thermal arrangement	DRL reduced maximum battery temperature and PCM temperature more effectively than NSGA-II and MOPSO	DRL demonstrated strong capability for advanced BTMS optimization
Kumar et al. (2023)	Review of battery management systems in EVs	Review of battery modelling, state estimation, and charging strategies	Discussed thermal control, voltage/current monitoring, balancing circuits, and research gaps	Improved BMS efficiency and reliability remained important research needs
Lakhotia et al. (2023)	Cooling strategies for EV battery thermal management	Review of air, liquid, hybrid, PCM, and heat-pipe cooling methods	Identified refrigerated liquid cooling with nanofluid heat pipes as highly efficient	Hybrid cooling systems offered improved thermal performance and battery safety
Altuntop et al. (2023)	Comparative analysis of BTMS cooling methods	Evaluated more than 200 research papers on BTMS performance	Hybrid cooling outperformed standalone passive and active systems	Hybrid BTMS provided better temperature control and reduced temperature variation
Ghalkhani et al. (2022)	AI and ML integration in battery systems	Review of battery design, thermal management, and AI-based BMS	AI/ML improved prediction of SOH, SOC, and SOP	Intelligent systems enhanced battery efficiency and thermal management
Fayaz et al. (2022)	Optimization of thermal and structural parameters in BTMS	Review of optimization techniques and cooling systems	Multi-objective optimization improved thermal performance, pressure drop, and system efficiency	Optimization algorithms were useful for improving LIB thermal stability and lifespan

Wang et al. (2022)	Review of battery cooling and heating systems	Comparative analysis of air, liquid, PCM, and heat-pipe cooling methods	Coupled cooling-heating systems showed strong future potential	Advanced coupled thermal systems improved safety and operational stability
Buidin et al. (2021)	Review of BTMS designs for lithium-ion batteries	Critical review of BTMS types and cooling technologies	Discussed advantages, limitations, and adaptability of various BTMS components	Effective thermal regulation improved EV efficiency and battery durability
Zhuang et al. (2021)	Intelligent cooling strategy for EV battery packs	Combined structural optimization with fuzzy model predictive control	Saved 76.4% energy and reduced temperature non-uniformity from 1.5°C to 0.6°C	Intelligent control methods significantly improved BTMS energy efficiency
Lin et al. (2021)	Review of thermal management models and cooling systems	Reviewed heat generation and temperature prediction models	Classified BTMS into air, liquid, and heat-pipe cooling systems and proposed CHAIN-based digital solution	Digital thermal management frameworks could improve battery safety and lifespan

Source: Secondary Source (Literature Study)

III. Input Parameters Used in Thermal Battery Management System Simulation

Parameter	Symbol	Value	Unit	Description
Simulation Time	t	0–1200	s	Total simulation duration
Time Step	dt	1	s	Simulation interval
Thermal Capacity	C_{th}	500	J/K	Battery heat storage capacity
Ambient Temperature	T_{amb}	298	K	Surrounding environmental temperature
Initial Battery Temperature	T_0	298	K	Initial battery temperature
Battery Current	I	50	A	Discharge current of battery
Internal Resistance	R_{int}	0.015	Ω	Internal resistance of battery
Heat Generation	Q_{gen}	37.5	W	Heat produced inside battery
No Cooling Coefficient	h_{no}	0.5	W/K	Heat dissipation without cooling
Air Cooling Coefficient	h_{air}	4	W/K	Heat transfer coefficient for air cooling
Liquid Cooling Coefficient	h_{liquid}	12	W/K	Heat transfer coefficient for liquid cooling

IV. Formulation

The battery heat generation was calculated using:

$$Q_{gen} = I^2 R_{int}$$

Calculation

$$Q_{gen} = 50^2 \times 0.015$$
$$Q_{gen} = 37.5\,W$$

Thermal Model Equation

The temperature variation of the battery was calculated using

$$\frac{dT}{dt} = \frac{Q_{gen} - h(T - T_{amb})}{C_{th}}$$

Where

- T= Battery temperature
- T_{amb}= Ambient temperature
- h= Cooling coefficient
- C_{th}= Thermal capacity
- Q_{gen}= Heat generated inside battery

Governing Thermal Equation

$$\frac{dT}{dt} = \frac{Q_{gen} - h(T - T_{amb})}{C_{th}}$$

Heat Generation Equation

$$Q_{gen} = I^2 R_{int}$$

V. Simulative Set up and Outcome

MATLAB was used for TBMS simulation.

Lithium-ion battery thermal behaviour was analysed.

Three cooling conditions were considered:

- Without Cooling
- Air Cooling
- Liquid Cooling

Simulation time was set from 0–1200 seconds.

Time step used was 1 second.

Battery current was maintained at 50 A.

Internal resistance was considered as 0.015 Ω.

Heat generated inside battery was 37.5 W.

Ambient temperature was maintained at 298 K.

Cooling coefficients used:

- No Cooling = 0.5 W/K
- Air Cooling = 4 W/K
- Liquid Cooling = 12 W/K

A mathematical model was designed using MATLAB for the Thermal Battery Management System (TBMS) to investigate and simulate thermal effect of lithium-ion batteries under various cooling conditions. Three cooling modalities, specifically without cooling, air ventilation and liquid immersion, were accounted in the simulation.

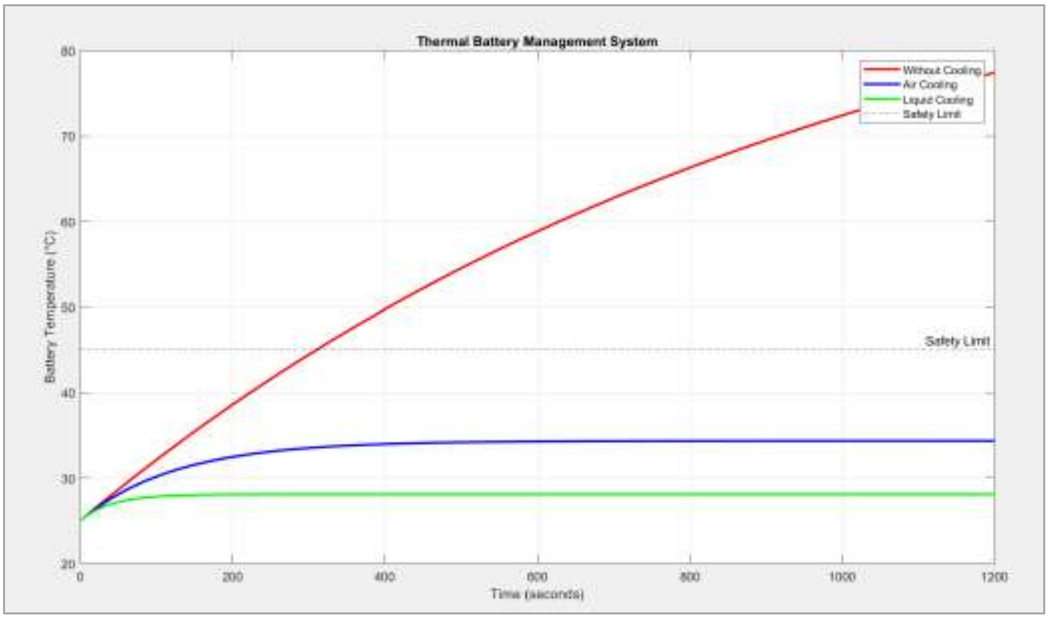

Figure 4.1: Temperature Response of Thermal Battery Management System under Different Cooling Methods

Source: Image Retrieve through MATLAB

The figure illustrates the battery temperature variation with respect to time under three different cooling conditions: without cooling, air cooling, and liquid cooling. The red curve corresponds to the battery working without cooling that is, the temperature monotonically increases and exceeds 45 °C, which leads it to thermally runaway (approximately reaching 77 °C after 1200 s). The blue curve corresponds to the air-cooling system, which cooled the battery pack limiting it around 34°C and ensuring safe operating conditions. Instead, the green curve displays the performance of the liquid-cooling system (the best case), which kept the battery nearly at 28°C for most of the simulated time span. The horizontal dashed line denotes the safe temperature limit. Results showed that liquid cooling had better heat dissipation and thermal stability than air cooling and no cooling conditions.

Outcome

Cooling Method	Final Temperature	Observation
Without Cooling	77.42 °C	Severe overheating
Air Cooling	34.37 °C	Stable operation
Liquid Cooling	28.12 °C	Best thermal performance

VI. Conclusion

The present study successfully demonstrated the importance and effectiveness of a Thermal Battery Management System (TBMS) for lithium-ion batteries using MATLAB-based simulation analysis. It was confirmed from the simulation that battery temperature had a significant dependence on cooling way during operation. The battery temperature raised rapidly and the safe operating limit was breached, with a quick rise to about 77.42°C being reached under the no-cooling condition; thermal runaway could have occurred in this case which would further decrease the lifetime of the battery. For air cooled, the method of passive cooling had good thermal conductivity so that quite moderate battery cooling performance could be achieved together with stable operation at an average battery temperature of 34.37°C. Liquid cooled the battery at approximately 28.12 °C because of its favourable thermal conductivity for rapid heat dissipation performance. The newly-developed thermal model and simulation algorithm, presented in this paper, describe the generation of heat from batteries as well as its cooling behaviour under a wide range of thermal conditions. This research advances electrically driven systems towards a more efficient, effective, and safer energy performance by proposing optimized cooling configurations and smart thermal management strategies for utilizing the latest technological advancements in electric vehicles and renewable energy applications. In conclusion, this study indicates that the liquid-cooled thermal management system is a potential seeker for next-generation lithium-ion battery applications due to their temperature requirements of safety and efficient regulation by comparison with air-cooled thermal management systems.

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