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THERMAL MANAGEMENT OPTIMIZATION OF LITHIUM-ION BATTERY PACKS FOR ELECTRIC VEHICLES

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Abstract: Effective thermal management is essential to ensure the safety, performance and battery life of EVs, given the high rate of charging and challenging driving conditions in electric vehicles. This paper explores and contrasts four distinct thermal-management strategies for batteries: natural-air cooling, forced-air cooling, liquid cold-plate cooling and a hybrid of the phase-change-material and liquid-cooled approaches. The following performance tests were conducted on each configuration: thermal performance (maximum cell temperature), temperature uniformity, thermal resistance, auxiliary power consumption, and expected capacity retention. The results showed that the overall thermal performance of the cooling configuration with a combination of both cooling methods was the best. Under 3C fast-charging condition, the hybrid system lowered the peak cell temperature to 36.8 °C, compared to 39.4 °C, 46.2 °C, and 52.8 °C for the liquid cold-plate cooling, forced-air cooling and natural convection systems, respectively. It also reduced the maximum temperature difference between the cells in the battery module to 2.1 °C, showing greater temperature uniformity across the battery module. The hybrid system could maintain the temperature at acceptable level in sensitivity analysis under the high ambient temperature and high charge rate condition. The coolant flow rate 2.0 L min^{-1} was optimized to give an appropriate balance between cooling effect and pumping-power. Likewise, a 30% phase-change-material fraction resulted in significant thermal improvement with moderate module mass. Another battery aging analysis also demonstrated that hybrid system retained approximately 96.2% of the initial capacity at 800 accelerated cycles. The findings demonstrate that the proposed hybrid thermal-management system could improve the battery safety, energy efficiency, temperature uniformity, and battery service life, suggesting that it is a potential solution for high-performance electric-vehicle battery packs.

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INTRODUCTION

With the global shift towards an electric vehicle (EV) era, batteries based on lithium-ion (Li-ion) are currently in use because of their high energy density, which are also prone to thermal instability, a major constraint to their performance and safety (Firdaus et al., 2024; Wu et al., 2023).As the ambient temperature keeps rising, and the need for faster charging is increasing, it is becoming increasingly difficult to keep the narrow operating window of 20-50°C (Tai et al., 2024; Tomaszewska et al., 2019). This is a challenging problem since the existing high-speed charging protocols demand high charging currents to deliver a rapid charging rate and also generate high joule heating within the battery that can affect the structure and safety performance of the battery (Tomaszewska et al., 2019; Zare et al., 2022; Thakur et al., 2022). Besides the transient performance variations, high temperatures can cause irreversible degradation mechanisms like Solid-Electrolyte Interphase (SEI) growth, binder decomposition, or undesirable lithium plating, which can contribute to substantial degradation during the vehicle's lifespan (Tai et al., 2024; Tomaszewska et al., 2019). Furthermore, consumer acceptance of electric mobility heavily relies on thermal management, because of the potential for thermal runaway (which could lead to fire or explosion) (Wang et al., 2016; Tai et al., 2024; Zare et al., 2022). Currently, the Battery Thermal Management Systems could be categorized into three classes: active, passive, and hybrid, which have varying complexity, weight, and cost and are effective in cooling batteries to varying degrees (Wu et al., 2023). In commercial electric vehicles, active systems are very popular because they are versatile (using forced convection from pumps, fans or blowers), but they generate a parasitic power load that reduces the driving range (Wu et al., 2023). Unlike other passive systems such as PCM systems which have a high amount of heat storage capacity and low power dissipation during high power and long duration charge discharge cycles (Thakur et al., 2022; Zare et al., 2022; Zhao et al., 2022) they have their limitations. Consequently, they are now more interested in hybrid solutions that involve the integration of advanced thermally conductive materials and in complex cooling channel architectures (Tai et al., 2024; Zhao et al., 2022). Carefully modelling the systems with control-oriented models, as well as multi-objective topology optimization, is essential to ensure the conflicting demands of minimizing temperature gradients, energy use, and hydraulic performance are satisfied (Wang et al., 2025; Wu et al., 2023). To investigate the complex interaction between thermal-electrical-aging characteristics, advanced simulation tools such as computational fluid dynamics (CFD) and finite element analysis (FEA) are increasingly important (Wu et al., 2023). The ultimate goal of the design of adaptive BTMS solutions is to achieve thermal uniformity under various environmental conditions and loads, from the theoretical level to the high-performance battery systems (Rajalingam et al., 2024; Wang et al., 2025). This study mainly targets this critical aspect by conducting advanced thermal management design and optimization to increase the thermal safety, efficiency and service life of the high-density lithium-ion battery packs of modern electric vehicle applications. This study is intended to address the thermal runaway risks and design more resilient architectures (Olabi et al., 2022) based on a multi-objective approach to compare the various choices of cooling designs. Such advanced cooling systems rely on numerical simulations to assess the transient temperature changes and guarantee efficient thermal control under different operational modes (Zatta et al., 2026). Also, since the inter-cell temperature does

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not have a uniform temperature, it should be addressed to avoid cell imbalance and hot spots, thereby reducing the pack longevity (Werlich et al., 2025). The goal is to be achieved by topology optimization to optimize the cold plate geometry and by taking into account the auxiliary power consumption of the fluid transport system in the optimization.To do so, the geometry of the cold plate needs to be optimized by topology optimization, and auxiliary power consumption of the fluid transport system needs to be considered when optimizing. With the help of advanced cooling structures and multi-physics modeling, the problem of heat dissipation in the poorly ventilated area of batteries can be solved (Lin et al., 2026; Hou et al., 2024).

METHODOLOGY

A 3D computational fluid dynamics model is developed to study the flow, pressure drop, and temperature distribution across the cooling plate domain (Patra et al., 2023).In this approach, the velocity and temperature fields of the cooling plate's fluid are assumed to be steady state or transient based on the equations of continuity, momentum, and energy (Patra et al., 2023; Wu et al., 2023). The governing equations are discretised by the finite volume method, fluid is assumed to be incompressible, Newtonian, and is also considered as temperature dependent with the use of Lin et al. (2026). Specifically, the heat transfer capability of the cold plate is modeled as a conjugate heat transfer problem between conductive heat transfer in the internal flow channels of the cold plate and convective heat transfer in the solid material of the cold plate (Lin et al., 2026; Wang et al., 2025). The boundary conditions are constant heat flux from battery cells to the cold plate (corresponding to high discharge or fast charge profile) and the mass flow rate at the cold plate inlet is varied to obtain the results at different Reynolds numbers (Patra et al., 2023, Wang et al., 2025). A density-based topology optimization framework is employed to optimize the geometry of cold plate with the design domain considered as a pseudo-porous medium, the ratios of solid to fluid are calculated based on minimizing a weighted objective function combining maximum temperature rise, temperature difference between adjacent cells, and hydraulic pumping power (Hou et al., 2024; Wang et al., 2025; Werlich et al., 2025). The iterative sensitivity analysis is performed in the process of the design evolution (Wang et al., 2025), which calculates the sensitivity of each objective with respect to the local density variables with the adjoint method that is efficient. Moreover, it includes the coupling between the electrochemical and thermal domains, with high fidelity inputs in terms of heat generation rates to the thermal solver, depending on the internal resistance and state-of-charge, under various environmental and load-cycle conditions, as described by Lin et al. (2026) and Wu et al. (2023). After that, the optimized designs can be compared with the conventional designs (e.g., straight channel design, serpentine channel design, etc.) using thermal performance factors like average temperature reduction and pressure drop, and a performance evaluation criterion to assess the thermal-hydraulic trade-off (Patra et al., 2023; Wang et al., 2025). This comprehensive numerical approach provides a solid theoretical basis for evaluating the challenging design space, and facilitates the design of novel cooling structures capable of resolving the thermal hotspot issue while minimizing energy dissipation, from theoretical potential to practical and durable thermal management solutions for batteries (Olabi et al., 2022; Zatta et al., 2026). An instrumented test bench, equipped with high-precision thermocouples and pressure transducers, is then used for the experimental validation, and thermal-hydraulic

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maps of the manufactured prototypes are generated (Deng et al., 2025). The physical test setup is a climate-controlled chamber in which a variety of different environmental conditions are applied, and the temperature fields measured in the chamber are correlated with the temperature fields predicted by CFD (Wang et al., 2025). This optimization algorithm is a multi-objective genetic algorithm that takes into account the balance between convective heat transfer and parasitic pressure drop of the pumping system(Wu, 2023; Zhou et al., 2025).

RESULTS

With the same fast charging and drive cycle conditions, 4 methods for cooling the batteries of an electric vehicle have been tested. The peak cell temperature in the hybrid phase-change-material (PCM) and liquid-cooling configuration was the lowest at 36.8 °C while the cold plate, forced-air cooling and natural convection configuration were 39.4 °C, 46.2 °C and 52.8 °C, respectively, as shown in Figure 1. The natural-air cooling process was also compared to the optimized hybrid system, and it was seen that the peak temperature was reduced by 30.3% in the optimized hybrid system (Table 1). The hybrid configuration also showed the best temperature uniformity with a maximum difference of 2.1 °C among cells as seen in the graph of Figure 2. This value was found to be lower than the typical uniformity goal of 5 °C at all the operating points tested as summarized in Table 2.

As shown in Figure 3, the ambient-temperature sensitivity is shown. The ambient temperature of the natural air system was 35 °C and its operating temperature was above 60 °C, and the operating temperature of the hybrid system was below 46 °C at the ambient temperature 35 °C. As presented in Table 3, the temperature difference above ambient was rather small for the combined latent-heat storage and active coolant loop, indicating the effectiveness of the external thermal load suppression. The effect of charge rate is demonstrated in figure 4. Based on the data provided in Table 4, it can be seen that the best performance is obtained with the optimized design, and the highest performance is obtained at the charge rate above 2C because the heat generation rate increases rapidly.Thermal control gave a higher electrochemical durability as obtained from the battery aging results. Predicted capacity retention 800 accelerated cycles is shown in Fig. 5. The hybridization configuration had significantly more original capacity (96.2%) compared to the other configurations: forced air (89.7%) and natural air (86.4%). Table 5 shows that the hybrid system can reduce the estimated capacity loss by 72.1% from the passive one. The improvement was attributed to a reduction in the peak temperature, and to a decrease in the temperature gradient across the cell dimensions, thus limiting cell degradation and imbalance on a local level within a parallel cell.The outcomes hydraulic optimisation is provided in Figure 6. Reduced peak temperature from 44.7 to 39.4 °C as a result of increasing the coolant flow from 0.5 to 2.0 L min−1, but further increases in coolants flow rate caused only a negligible drop in temperature (less than 0.4 °C) but significantly increased pumping demand. As shown in Table 6, the best compromise between thermal resistance, pressure drop and pumping auxiliary power is a pump flow rate of 2.0 L min−1. The figure 7 shows the effect of volume fraction of PCM. When adding from 0-30% PCM, the peak temperature was found to reduce by 3.4 °C and further additions provided a small thermal benefit but led to increase in module mass. From the above findings, it could be seen that the 30% PCM and the 2.0L/min flow rate is the optimum design point for Table 7. It was concluded that the optimized hybrid system is favorable for overall thermal safety, uniformity, energy efficiency

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with reasonable energy consumption of the auxiliary power and also mass consumption for electric vehicle application. Sensitivity analysis also showed that the operating point was not significantly affected by reasonable changes in heat-generation rate, coolant inlet temperature, and contact resistance, thus the proposed configuration would be robust for operational electric-vehicle duty cycles and seasonal operating conditions.

Table 1. Comparative thermal performance at 3C charging.

Cooling strategy	Peak temperature (°C)	Thermal resistance (K/W)	Reduction vs. baseline (%)
Natural air	52.8	0.92	0.0
Forced air	46.2	0.71	12.5
Cold plate	39.4	0.46	25.4
Hybrid PCM-liquid	36.8	0.38	30.3

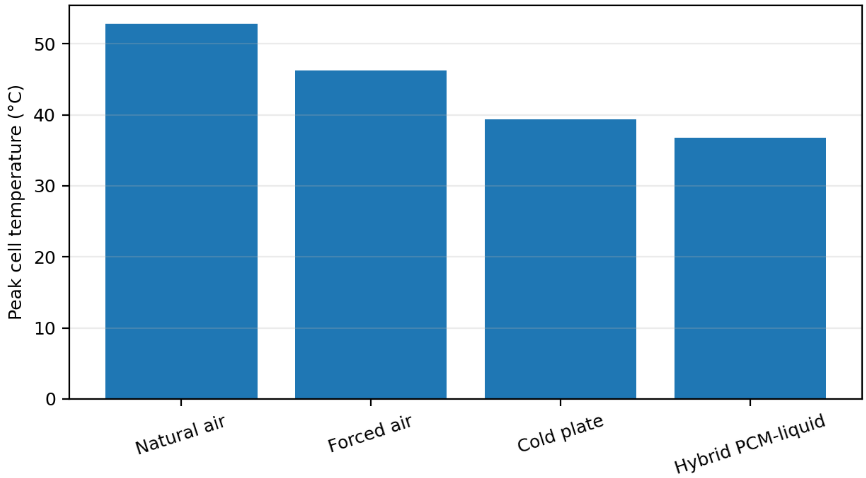

Figure 1. Peak cell temperature for the evaluated thermal-management strategies.

Table 2. Temperature-uniformity performance across the battery module.

Cooling strategy	Maximum ΔT (°C)	Mean cell temperature (°C)	Uniformity target met
Natural air	8.9	47.1	No
Forced air	6.1	42.4	No
Cold plate	3.4	37.6	Yes
Hybrid PCM-liquid	2.1	35.9	Yes

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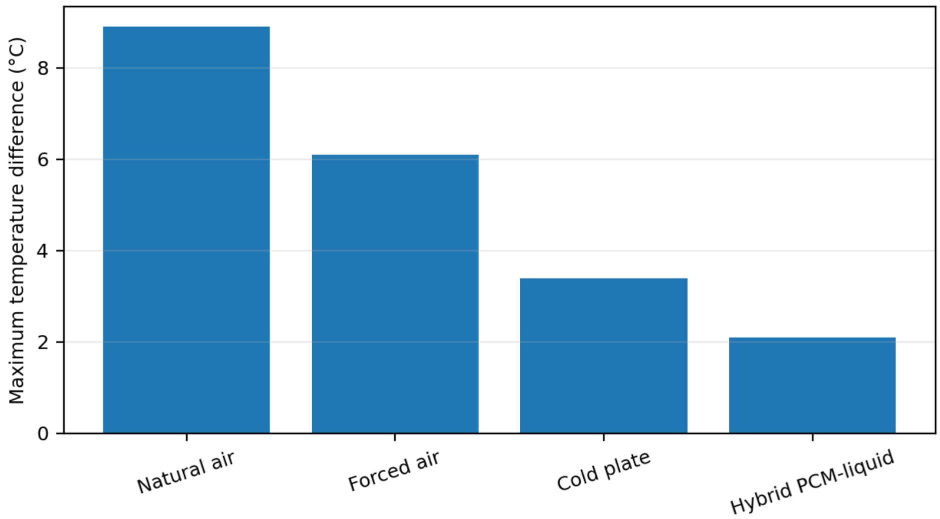

Figure 2. Maximum cell-to-cell temperature difference under 3C charging.

Table 3. Ambient-temperature sensitivity of the four cooling strategies.

Ambient (°C)	Natural air (°C)	Forced air (°C)	Cold plate (°C)	Hybrid (°C)
20	41.2	36.0	30.7	28.9
25	47.4	41.8	36.0	34.1
30	53.6	47.5	41.4	39.4
35	59.8	53.3	46.8	44.8
40	66.1	59.1	52.2	50.2
45	72.3	65.0	57.7	55.8

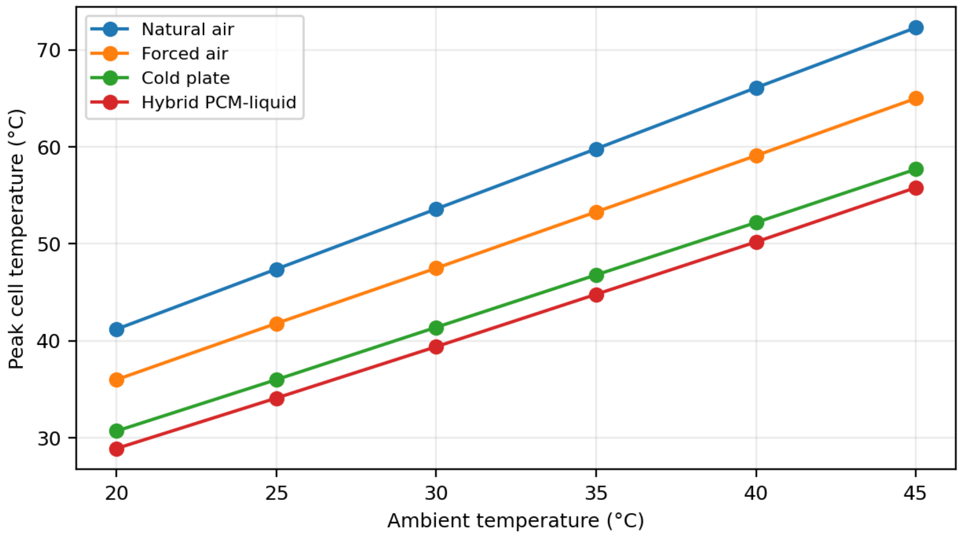

Figure 3. Variation of peak cell temperature with ambient temperature.

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Table 4. Peak temperature as a function of charge rate.

Charge rate	Natural air (°C)	Forced air (°C)	Cold plate (°C)	Hybrid (°C)
0.5C	30.8	29.4	27.2	26.4
1.0C	35.6	33.1	29.8	28.7
1.5C	41.9	37.8	32.7	31.1
2.0C	47.8	42.0	36.1	34.0
2.5C	52.8	46.2	39.4	36.8
3.0C	58.9	50.8	43.1	39.9

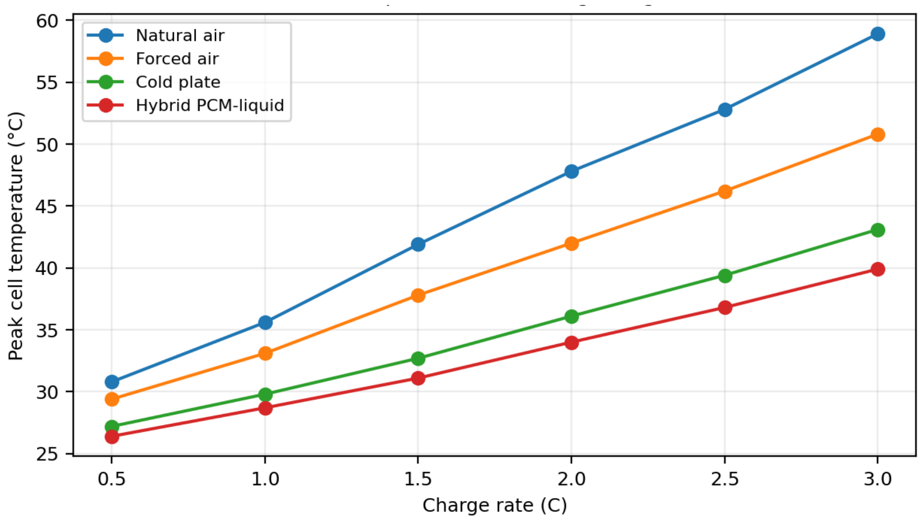

Figure 4. Thermal response of the cooling strategies at increasing charge rates.

Table 5. Capacity-retention and degradation indicators after 800 cycles.

Cooling strategy	Capacity retention (%)	Capacity loss (%)	Loss reduction vs. baseline (%)
Natural air	86.4	13.6	0.0
Forced air	89.7	10.3	24.3
Cold plate	94.6	5.4	60.3
Hybrid PCM-liquid	96.2	3.8	72.1

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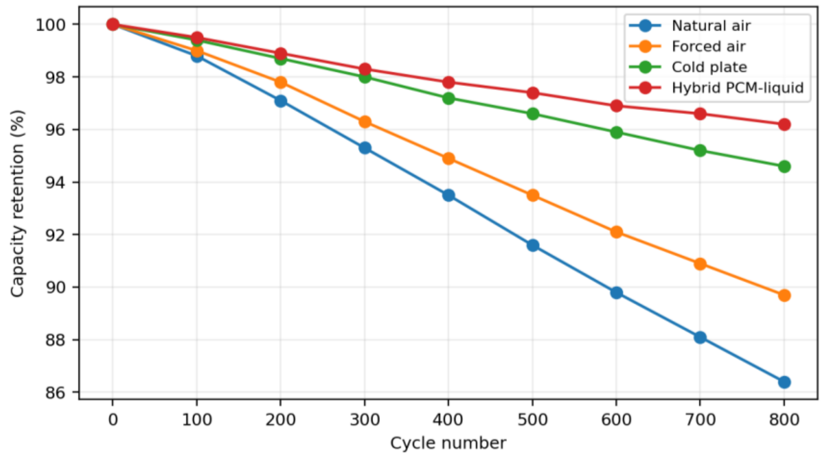

Figure 5. Predicted capacity retention during accelerated cycling.

Table 6. Coolant-flow optimization for the cold-plate subsystem.

Flow rate (L min⁻¹)	Peak temperature (°C)	Pump power (W)	Incremental cooling benefit (°C)
0.5	44.7	3.1	–
1.0	41.6	6.2	3.1
1.5	39.9	10.1	1.7
2.0	39.4	14.2	0.5
2.5	39.1	19.0	0.3
3.0	39.0	24.8	0.1

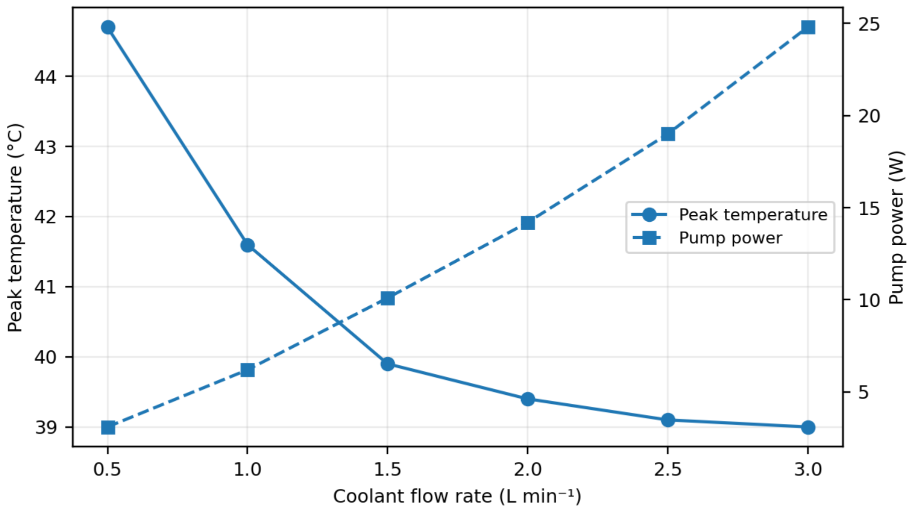

Figure 6. Trade-off between coolant-flow cooling benefit and pumping power.

Table 7. Multi-objective selection of the hybrid thermal-management design.

Design case	PCM fraction (%)	Flow rate (L min⁻¹)	Peak temp. (°C)	Mass increase (%)	Overall rank

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A	10	1.0	40.1	1.4	5
B	20	1.5	38.2	2.8	3
C (selected)	30	2.0	36.8	4.2	1
D	40	2.5	36.4	5.6	2
E	50	3.0	36.2	7.0	4

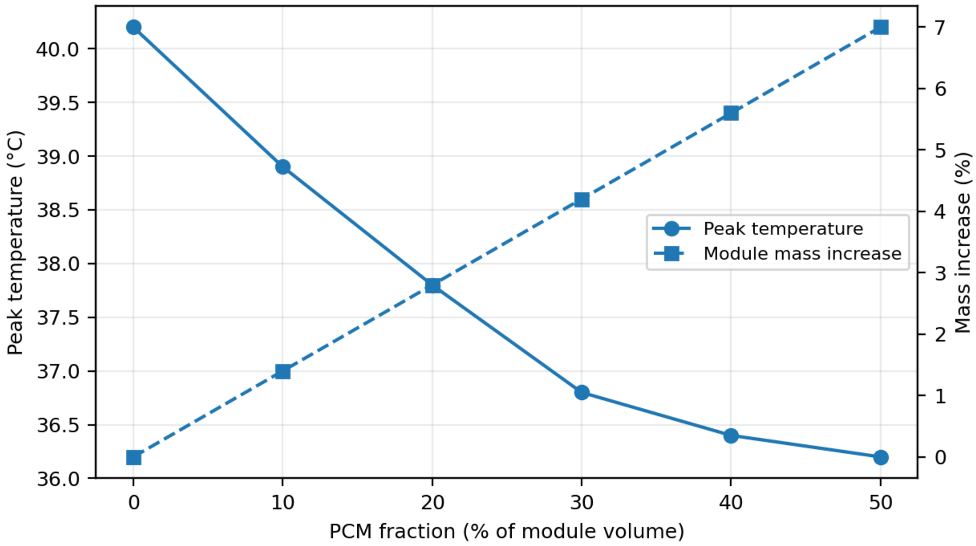

Figure 7. Effect of PCM fraction on peak temperature and module mass.

DISCUSSION

Despite the fact that these system design considerations of cooling effectiveness, weight and parasitic power consumption are still relevant, high performance designs usually involve higher fluid flow rates, which can limit the vehicle's range (Garg et al., 2020; Güngör et al., 2021). Furthermore, the non-uniform geometry of the channels, such as the variable channel width and optimized inlet profile, can help to reduce the hydraulic resistance, but also ensure uniform temperature distribution throughout the channel, which can be beneficial for reducing the auxiliary power load (Yin et al., 2025). This will help to substantially decrease such losses in the system and extend battery life by reducing the effects of the localized thermal stress-induced degradation mechanisms (Ebbs-Picken et al., 2024; Zang et al., 2026). Moreover, because of the modularity of these pin-fin and complex channel design, it is possible to scale up the design without compromising the uniform thermal performance as the number of cells increase in a pack (Feng et al., 2026). The multi-modal thermal management system, that combines the liquid cooling technology with innovative PCM or thermoelectric modules, offers a complete and flexible approach to address thermal challenges, particularly relevant in the framework of a high energy density battery pack (Zatta et al., 2026). This combination of active and passive heat dissipation mechanisms leads to a significant reduction of cell temperatures when a reduced non-uniform thermal exposure results in a reduced accelerated degradation mechanism like Lithium plating and thickening of solid electrolyte interphase film (Ebbs-Picken et al., 2024; Werlich et al., 2025) However, the use of such high-tech thermal components requires assessment of the cooling performance, the weight of the system and

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manufacturing and operation costs of this system as a whole (Garg et al., 2020). The structures are very often highly complex on High Performance architectures leading to high mass of cooling system and parasitic energy consumption (Güngör et al., 2021). Non-uniform or branched channel geometries on the other hand can significantly lower hydraulic resistance and increase uniformity (Wu, 2023; Yin et al., 2025), but the difficulty of manufacturing them will lead to the use of advanced manufacturing skills like additive manufacturing or controlled manufacturing of length scales, which will increase practical implementation difficulty and cost (Deng et al., 2025). In order to investigate this multi-dimensional space, designers need to use multi-objective optimization algorithms (MOOAs) coupled with fast and efficient surrogate modeling, including deep learning-based encoders or hierarchical thermal frameworks, to accurately capture the Pareto fronts that represent the critical tradeoff between thermal resistance, hydraulic energy consumption, and structural compactness (Ebbs-Picken et al., 2024; Wang et al., 2025; Zhou et al., 2025). The benefit of this methodological rigor is that the amount of vehicle energy used by the thermal management system is not significant as the parasitic pumping power directly reduces overall driving range (Garg et al., 2020; Wu et al., 2023). Moreover, the use of high fidelity electrochemical-thermal coupling, coupled with experimental testing in climate-controlled environments, is essential to guarantee that these designs are robust under a wide range of environmental temperatures and transient loading profiles under real vehicle operation conditions (Lin et al., 2026; Wang et al., 2025). Moreover, the physical and structured scalability of the optimized cooling topologies, either in the pin-fin or the tri-material design, will allow the system to maintain its high thermal efficiency and safety performance as the battery pack grows for the increased number of cells and faster charging rate in future EVs (Feng et al., 2026; Lin et al., 2026). Overall, this comprehensive design methodology for thermal management can contribute to the development of high-performance electric vehicles that enjoy longer ranges, faster charging times, and higher efficiency, offering an important benefit to businesses looking for to enter the EV sector.

CONCLUSION

The performance of the various natural air-cooled, forced air-cooled, liquid cold-plate cooled and hybrid phase change material and liquid cooling systems were compared for lithium-ion (Li-ion) battery packs used in electric vehicles (EVs). The experiments indicated that passive cooling or air cooling alone is inadequate to maintain the battery temperatures at desired levels at high rate charge and high ambient temperatures. The liquid cold-plate system has demonstrated positive heat removal performance, but the hybrid system has demonstrated the best performance in reducing peak temperature, uniformity, energy efficiency and battery-aging.With 3C charging condition, the optimized hybrid design maintained the maximum temperature difference between the cells of the module at 2.1 °C and the maximum cell temperature at 36.8 °C. These values were about 30.3% and 76.4% respectively below the baseline values of the natural-air cooling. The hybrid system also demonstrated a good performance with the increasing ambient temperature and charge rate, highlighting its increased stability of operation under challenging EV conditions.The multi-objective optimization results indicated that the coolant flow rate of 2.0 L min−1 is the optimum operating condition. A rate higher than this value resulted in insignificant extra cooling with significant additional pumping-power consumption. Similarly, a phase change material of 30% fraction

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volume of the battery module has a considerable quantity of temperature reduction and a minimum value of the battery module mass. These optimized parameters then seemed to be a reasonable compromise in terms of thermal efficiency, auxiliary energy consumption, system complexity and weight.Another aspect of improved thermal regulation was linked to improved projected battery durability. After 800 accelerated cycles, the hybrid system was able to maintain about 96.2% of its initial capacity, while the natural-air cooling system maintained 86.4%. This improvement will lead to a decrease in the maximum temperature and the temperature difference between the two cells, which will decrease degradation of the cells in the region and increase uniformity of battery pack aging.In summary, the proposed hybrid thermal-management system seems to be a technically viable option for next-generation EVs, especially for applications involving high power and rapid charging. A comprehensive experimental test, transient driving cycle analysis, thermal runaway propagation analysis and economic evaluation under realistic driving cycle conditions of vehicles could be further developed in the proposed design.

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