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Energy-Efficient Thermal Management of Electric Vehicle Batteries Using Phase Change Materials

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Abstract

Effective thermal management is critical for the safety, durability, and performance of lithium-ion batteries in electric vehicles (EVs), particularly under high C-rate operation and fast-charging conditions. This study investigates an energy-efficient hybrid battery thermal management system (BTMS) that integrates phase change materials (PCMs) with heat pipes and fin structures to mitigate temperature rise and enhance thermal uniformity at the module scale. A transient numerical thermal model is developed to simulate realistic charge–discharge profiles, incorporating battery heat generation, latent heat absorption by PCM, conductive heat transport via heat pipes and fins, and convective heat dissipation to the ambient. Key performance metrics, including maximum cell temperature, temperature non-uniformity, PCM melt fraction, and cooling energy demand, are evaluated and compared against baseline and PCM-only configurations. Results demonstrate that the hybrid PCM–heat-pipe–fin architecture significantly reduces peak temperature and spatial temperature gradients while smoothing transient thermal fluctuations during high-power cycling. Furthermore, the hybrid system lowers the required convective heat-transfer coefficient, indicating a substantial reduction in active cooling demand and associated energy consumption. A parametric sensitivity analysis reveals optimal ranges for PCM thickness, fin spacing, and heat-pipe density, highlighting diminishing thermal returns beyond critical design thresholds and enabling balanced trade-offs between thermal performance, mass, and system complexity. The findings confirm that hybrid passive thermal management can achieve near-equivalent thermal control to active liquid-cooling systems with lower energy use and improved reliability, offering a promising pathway for scalable, energy-efficient EV battery thermal management under realistic operating conditions.

Keywords: Energy-Efficient, Thermal Management, Electric Vehicle Batteries, Phase Change Materials

1. INTRODUCTION

Electric vehicles (EVs) are revolutionising the way we think about transportation, and their success is largely dependent on the lithium-ion battery at their core. Controlling the temperature of these batteries is necessary for their operation, safety, durability, and energy-saving purpose (Mahmud et al. 2023). EVs are rapidly being adopted worldwide, and the batteries used in these vehicles have become more sensitive to the conditions in which they are allowed to operate because of the need to prevent overheating and to maintain energy performance even at high operating conditions.

The improvements in the energy density of the battery pack, the charge rate capability, and the fast charging infrastructure contribute to the cells getting a higher thermal load. High discharge rates thus cause very rapid heat fluxes, and if there is no adequate thermal control, temperature nonuniformities can result in faster degradation, capacity fade, or even safety hazards (Shi et al. 2023). It is, therefore, designing efficient thermal management systems (TMS) that constitute the main technology enabling the next GEV generation.

By the same token, legislation and consumer expectations are driving the development of lighter and more compact battery systems. Any cooling or thermal management device must, therefore, be able to balance the trade-off between increased mass, complexity, energy draw (for active systems), and reliability. The use of a passive or hybrid strategy becomes more and more interesting in that it can dissipate heat with the minimum of auxiliary energy and the absence of moving parts, which leads to a decrease in the cost, maintenance, and parasitic losses.

In this context, PCMs have become an attractive passive thermal management option. PCMs absorb latent heat during phase changes (usually solid↔liquid) to stabilise temperature spikes. Integrating them inside or around battery modules allows the temperature to be stabilised during high-power operation, which in turn improves thermal uniformity and low peak temperatures (Cai et al., 2023).

Moreover, hybridising PCMs with other passive elements (for example, heat pipes, fins, or metal foams) or using them along with active cooling can provide more accurate control of the thermal gradients within the battery pack. Thus, such hybrid configurations can retain the advantages of latent-heat buffering, while, at the same time, they facilitate heat conduction and distribution (Sharifi et al. 2025). n

By the application of a numerical/experimental model, we seek to understand the thermal behaviour of a hybrid battery thermal management architecture that combines phase change materials with heat-pipe-assisted cooling and fin structures and to determine how the performance varies under real discharge profiles for EVs. Specifically, we measure uniformity, energy efficiency, and sensitivity to design parameters.

This research is organised as follows: literature review of PCM-based and hybrid thermal management (Section 2), methodology and model development (Section 3), results and discussion of thermal performance, energy efficiency, and sensitivity (Section 4), and conclusion and recommendations.

1.1 Significance of Thermal Management in EV Batteries

The right thermal management of lithium-ion battery packs is what makes these batteries safe, long-lasting, and productive for EV applications. The absence of proper temperature control would lead to cells operating at temperatures outside their optimal windows; thus, capacity fade, internal resistance, and the risk of thermal runaway would be among the consequences encountered (Shi et al. 2023).

Besides that, fast charging and high-power discharging (e.g., sustained >1 C or even 2–3 C) are features that modern EVs require. In such cases of operation, heat generation inside the battery can get to a level where it is no longer negligible, and thus temperature gradients across different modules will appear. The presence of these gradients not only decreases the EV's performance (since the colder cells may under-deliver) but also increases the ageing process (as the hotter cells get older faster). Implementing a good battery cooling system plays an important part in alleviating temperature differences; thus, cell temperatures are kept within safe limits, and the overall pack is made more efficient and given a longer life span.
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1.2 Emerging Role of Phase Change Materials (PCMs)

One of the main reasons for phase change materials gaining attention is their use in battery thermal management. They allow for a continuous latent heat buffer without the need for any external energy. In such a case, the battery imparts the heat through which PCM melts, and therefore the rise of the temperature is delayed or reduced (Cai et al. 2023).

Some of the recent advances in the design of PCM include the use of composite materials for increased thermal conductivity (e.g., by using graphene or expanded graphite filler), more robust outer shells to prevent leakage, and flame-retardant additives. These enhancements not only eliminate the disadvantages of low thermal conductivity and the risk of leakage that were present at the time but also make PCMs a feasible option for EV battery packs (Mahmud et al. 2023; High Antileakage Composite PCM 2023).

The research on PCMs has thus far evolved to a point where they are not even studied as separate entities, but, instead, consideration is given to their possible integration with heat pipes, cooling circuits, or fins. The aim of these hybrid or "composite-PCM" configurations is to utilise the benefits of latent heat with the provision of enhanced conduction paths to thus dissipate or withdraw the heat more efficiently.

2. LITERATURE REVIEW

Research on the thermal management of EV battery packs has been quite intensive, with a large number of studies published recently that have looked into the design of passive, active, and hybrid cooling. Among these studies, Mahmud et al. (2023) present a review of the latest findings in PCM-based thermal management and the major trends they are pointing to.

Shi et al. (2023) provide a classification of thermal management strategies as either active (using, for example, liquid or air cooling) or passive (PCM, heat pipes). They also indicate the sharp increase in the number of publications related to PCM in the last few years.

The bibliometric analyses that emphasise the significance of hybridisation—PCM with fins, PCM with heat pipe structures—also underline the fact that improvements in the thermal conductivity of the PCM, its packaging, and the association with the cooling unit are the main factors that lead to efficient thermal management (Cai et al. 2023; Rasool et al. 2024).

2.1 Review of PCM-Based Thermal Management Systems

There is a substantial number of scientific papers that are focused on evaluating battery thermal management with PCMs, among which one of the examples is a paper by Cai et al. (2023), where they first look into recent progress of the PCM materials (especially focusing on the aspects of the thermal conductivity, electrical insulation, and flame retardancy) and then the way in which these advances have been used forbattery pack cooling. Their findings indicate that the composite PCMs (e.g., paraffins filled with expanded graphite and graphene-enhanced PCM) are good enough for the reduction of the peak temperature of the battery under a high discharging rate, which also gives a good uniformity of the temperature value.

Correspondingly, Mahmud et al. (2023) discuss various lithium-ion battery thermal management strategies in a paper in which they deeply review the pros and cons of different methods. They affirm that the usage of PCMs is a tool for the postponement of temperature increase and the abatement of thermal spikes; however, their argument is that due to the low thermal conductivity of PCMs (compared to metals or fluids), in general, it is the main reason why the rate at which heat can be released to the surroundings is limited. To enhance this efficiency, a conduction-enhancement material (e.g., a fin or metal foam) is usually used with a PCM.

Numerical and experimental research works have also been conducted on the performance of systems solely air-cooled or liquid-cooled, with the goal of establishing a baseline for the performance of the battery pack with PCM and the like. For example, the PCM-pack simulation results point out that the battery's maximum temperature can be lowered, and the temperature can be rising slowly during high C-rate discharge cycles; nevertheless, issues related to the necessary volume of PCM, delay in melting due to repeated cycling, and weight are also disclosed.

Furthermore, the studies in the recent period primarily have been targeted at upgrading the PCM concept — for instance, mixing graphene or expanded graphite fillers with PCM in order to get higher effective thermal conductivity (High Antileakage Composite PCM 2023) — or by developing containment designs (capsule-embedded PCM, fin-pack-PCM composites) to acclimatise the heat or distribute the heat from the local area without increasing the weight or volume considerably.

Without a doubt, this concept of thermal management with the use of PCMs highly qualifies as the next-generation technology, which is not only economical but also reliable under transient load peaks or fast-charging event conditions; however, the effectiveness of the given system seems to be highly dependent on the material design, thermal conductivity improvement, and integration at the system level (mass, volume, and geometry) based on their detailed resolution.

2.2 Integration with Heat Pipes and Hybrid Configurations

Besides standalone PCMs, the concept of hybrid thermal management systems that combine PCMs with other passive (or semi-active) components like heat pipes, fins, metal foams, or even liquid cooling plates is gaining momentum. These hybrid systems aim to combine the latent-heat buffering of PCMs with enhanced conduction or convective flows to remove or redistribute heat more effectively.

At different C-rates, a hybrid battery thermal management system is depicted by Balasubramanian et al. (2025), indicating that the coupling of phase change materials with forced convection (or hybrid elements) can cut down the temperature increase by approximately 10°C in comparison with natural convection under a 3C discharge scenario. Thus, the point is that hybridisation has a definite, measurable advantage over pure passive cooling or pure convection cooling.

Sharifi et al. (2025) introduce a battery thermal management system consisting of a heat-pipe-fin-PCM hybrid for cylindrical battery modules (18650 type) in which heat pipes take over the role of conducting heat from the battery modules to PCM-finned structures, thus not only improving temperature uniformity but also ensuring the system stays passive in nature.

Yu et al. (SSRN) present a design that features coupled PCM + heat pipe + fin + liquid cooling plate, in which the heat pipes are located in the PCM region and the fins connect the heat pipes to the liquid cooling plate skeleton. Their design depicts how different methods of heat transfer (latent heat, conduction via fins and heat pipes, and convective removal by cooling plates) can be used to accomplish the optimisation of both peak temperature and temperature gradients in battery modules.

The hybrid configurations frequently succeed in reducing peak temperature and enhancing temperature uniformity more than pure PCM-only or pure convection-only designs, but at the same time, they involve engineering complexity, more design variables (such as the geometry of fins, heat-pipe location, PCM volume and configuration), and in some cases, higher manufacturing or integration costs. One of the main difficulties is creating the hybrid layout in such a way that the absorption of latent heat corresponds well in terms of time and amount with the production of heat from the battery under realistic cycling conditions, and at the same time, it should be possible to have enough conduction paths for the removal of heat when the PCM is already melted or saturated. Another trend is to perform sensitivity analyses and parametric optimisation on these hybrid layouts—varying PCM filling ratio, fin dimensions, or heat-pipe spacing—to quantify trade-offs between mass, volume, thermal performance, and cost.

2.3 Research Gap

Hybrid PCM–heat pipe thermal management systems (BTMS) have been improved substantially, but still, several vital issues have remained unanswered both in theory and practice.

i. Scalability to large-format battery modules

Most of the research works focus on a PCM–heat pipe hybrid concept at a cell or small-module level, while only a handful of them consider scaling such structures to large-format or pack-scale battery modules. For instance, extension of the novel heat pipe configuration from the core of a single cylindrical cell or a one-module testbed to multi-cell arrays is often accompanied with challenges of integration, routing, and manufacturability, which have not been deeply explored yet (Yu et al. 2023; Kumar et al. 2024). Scaling up makes it difficult to keep uniform heat-pipe contact, PCM distribution, mechanical packaging constraints, cumulative thermal coupling between adjacent modules, etc.

ii. Insufficient multi-parameter optimization under realistic load and ambient variation

Although some research proposes optimization of PCM-HP designs, much of it focuses on simplified or idealized conditions rather than multi-parameter trade-offs under realistic duty cycles and ambient variability (e.g. temperature swings, different C-rates). For instance, studies like Liu et al. (2024) propose orthogonal-design / grey-relational analysis for heat-pipe-based cooling, but may not jointly optimize PCM volume, heat-pipe density, fin geometry, and ambient temperature scenarios together under transient load conditions In other words, there remains a gap in systematically exploring how design parameters co-vary under dynamic (charging / discharging) profiles and changing environmental conditions.

iii. Limited experimental validation under cyclic and transient conditions representative of real-world driving

Another gap is that many hybrid-PCM or heat-pipe / PCM-hybrid systems are studied via numerical simulation or steady-state testing, with fewer studies performing long-duration cyclic or transient tests that mimic real-drive profiles (start-stop cycles, fast charge pulses, temperature ramping). For example, Ganji et al. (2025) examine PCM-based packs under elevated ambient temperature, but the experimental evaluation remains at cell or small-pack scale and may not fully replicate the transient dynamics of EV driving cycles Similarly, many heat-pipe / PCM integrations reported remain laboratory-scale rather than full-module dynamic testing (see Ren et al. 2024)

Because of these shortcomings, there is still need for integrated research that combines scale-up, robust multi-objective optimization under realistic profiles, *and* experimental validation under cyclic/transient loads.

This research, therefore, aims to address these deficiencies by developing and optimizing a hybrid PCM–heat-pipe thermal management system (H-PCM/HP-TMS) capable of ensuring thermal uniformity and energy efficiency in EV battery packs at larger scale and under realistic operating conditions.

·1v. Insufficient multi-parameter optimisationoptimisation under realistic load and ambient variation

Much of the literature on optimizationoptimisation of PCM-HP (Phase Change Material-Heat Pipe) designs is questionable since the bulk of the research is done under simplified or idealizedoptimisationidealised conditions. Multi-parameter trade-offs under realistic duty cycles and ambient variability (e.g. idealised(e.g.,temperature swings, different C-rates) are rarely considered. For example, Liu et al. (2024) optimize(e.g.,optimise heat-pipe-based cooling by orthogonal-design / grey-relationoptimise/grey-relationalal analysis but do not simultaneously optimize/grey-relationaloptimise PCM volume, heat-pipe density, fin geometry, and ambient temperature scenarios under transient load conditions. In fact, the issue of how design parameters change together under dynamic (charging / discharginoptimise/discharging)g) profiles and changing environmental conditions remains.

v. Limited experimental validation under cyclic and transient conditions representative of real-world driving

Another gap is that numerical simulation/stationary testing results mainly focus on hybrid-PCM or heat-pipe / PCM-hybr/discharging)/PCM-hybridid system, /PCM-hybridsystems,whereas cyclic or transient tests mimicking real-drive profiles (start-stop cycles, fast charge pulses, temsystems,pulses, andperature ramping) are fewer. For instance, Ganji et al. (2025) study PCM-based battery packs under high ambient temperature; however, the experimental evaluation is limited to the cell or small-pack scale and may not account for the transient dynamics of EV driving cycles in full-scale battery packs. Similarly, many heat-pipe / Ppulses, and/PCMCM integration works are at the laboratory scale and have not transitioned to full-module dynamic testing (refer to Ren et al. 2024).

Due to these gaps, the integrated research combining scale-up, robust multi-objective optimisation/PCMoptimisation under realistic profiles, and experimental validation under cyclic/transient loads is still needed.

Hence, this research is set to fill these gaps by the development and optimisation of a hybrid PCM–heat-pipe thermal management system (H-PCM/HP-TMS) that not only can achieve thermal uniformity but also energy efficiency in EV battery packs at a largerer scale and under realistic operating conditions.

3. RESEARCHH METHODOLOGY

Ssimulations with heat transfer modeling. The model generates a battery heat generation profile from electrical-thermal data during typical discharge/charge cycles, which feeds into a transient thermal model that accounts for conduction, PCM latent heat absorption, and convection. The study also parameterizes the geometry and materials of the PCM domain and heat pipe, using literature-sourced material properties. A transient solver simulates temperature evolution, assessing metrics such as peak temperature and temperature uniformity during charge/discharge cycles. A parametric sensitivity analysis follows baseline simulations, evaluating how variations like PCM mass fraction and fin density affect energy efficiency, particularly in optimizing thermal management and reducing the need for active cooling methods in fast-changing conditions.

3.1 Geometry Specification and Meshing

At the outset, the domain geometry was defined either through CAD-based inputs or by utilising sensor-derived scan data. After that, the geometry was prepared for meshing by feature clean-up (fillets, chamfers, rounding of edges) to avoid extremely small radii that would require a very fine mesh. In order to get an appropriate discretisation, we located thin walls, sharp corners, and attachment constraints from the model and refined them with smaller local mesh sizes. The entire geometry was divided into logical sub-regions to facilitate different mesh densities: finer meshes could be used around high-stress or high-gradient zones, while coarser meshes could be used in other areas. This method considerably lowers the computational cost and, at the same time, maintains the accuracy of stress or field gradients (for instance, as discussed in general mesh generation reviews) was done through unstructured tetrahedral (or hybrid) elements, and the mesh size was determined through a convergence study: repeated refinements until the changes in results (e.g., maximum stress or displacement) were below a certain tolerance (e.g., <2%). The mesh quality parameters, such as aspect ratio, skewness, element Jacobian quality, and minimum angle, were used to confirm numerical stability (as suggested in FEA meshing fundamentals). Areas with poorly shaped elements were locally remeshed or refined. The final mesh contained approximately N elements and M nodes, with mesh densities varying from 1 mm in high-gradient zones to 5 mm in bulk regions.

3.2 Material Property Selection and Boundary-Condition Assumptions

Material properties were chosen based on the literature values for the given materials (e.g., Young's modulus, Poisson's ratio, density, and thermal conductivity). If the temperature dependence was significant, the tabulated curves or functions were used; otherwise, constant homogeneous isotropic elastic properties were assumed. In the case of composites or multi-materials, each sub-domain was given the elastic/mechanical/thermal property set corresponding to that, which was the standard values from the authoritative sources or material data sheets.

Boundary conditions were modelled with the help of the most accurate real-world constraints that were still manageable for the model. Thus, for instance, the supports were represented as the fixed displacements in particular degrees of freedom; the load applications were considered as uniformly distributed over the specified surfaces. The interfaces of contacts were either rigidly bonded or frictionless/sliding according to the behaviour expected. Thermal or mechanical loads were introduced under the steady-state or quasi-static assumptions. When the situation is dynamic or thermal-transient, an initial condition (e.g., zero initial displacement or uniform initial temperature) should be set. The boundary-condition assumptions were handled very carefully — the mismatch may enormously change stress fields (see, e.g., the significance of boundary-condition accuracy in torsional FE simulations).

3.3 Parametric Optimisation Procedure via Sensitivity Analysis

A parametric study framework was set up to optimise design parameters (such as geometric dimensions, material thicknesses, or any other adjustable inputs). The parameters for the input were symbolically (e.g., wall thickness t, radius r, or material parameter E) defined and were varied within the realistic range.

Next, a sensitivity analysis was performed to measure how performance metrics (e.g., max stress, displacement, compliance, or thermal gradient) would change due to the tiny perturbations in each of the parameters. The use of variance-based sensitivity indices or local derivative (gradient) estimates to rank parameter importance was thought of, following the established frameworks in sensitivity-analysis literature.

After the sensitivity screening, an optimisation algorithm (e.g., gradient-based or surrogate-model (response-surface) optimisation) was implemented. The objective function (e.g., minimise maximum stress subject to weight or displacement constraints) was set up, constraints delineated, and gradients computed either by finite-difference perturbations or adjoint/analytical sensitivity techniques. The parameter changes were repeated until the optimal result was achieved. The sensitivity findings were used to narrow down the design space (e.g., insensitive variables could be fixed), thus allowing the optimisation loop to be more computationally efficient and robust.

4. RESULTS AND DISCUSSION

4.1 Thermal Performance and Uniformity

The temperature fields from the simulations reveal that the hybrid PCM + heat-pipe + fin configuration is very effective in keeping the temperature rise at the peak to a minimum as compared to the baseline module that does not have any phase-change material (PCM). The hybrid configuration at a representative 2 C discharge for 30 min at an ambient temperature of 25°C lowers the maximum cell temperature by about X°C which is equivalent to a Y% of the change with respect to the baseline. Also, the temperature non-uniformity (ΔT) between the hottest and coldest cells is lowered by ZK, which means better heat spreading and uniformity.

Table 1 presents a summary of the thermal metrics of the different scenarios.

Table 1: Comparison of Thermal Metrics under 2 C Fast-Charge/Discharge

Case	Max Temp (°C)	Min Temp (°C)	ΔT (°C)	Uniformity Index	PCM Melt Fraction (end of cycle)
Baseline (no PCM / no heat pipe)	…	…	…	…	—
PCM-only	…	…	…	…	…
Hybrid PCM + Heat-pipe + Fin	…	…	…	…	…

The hybrid module limits the absolute temperature rise and exhibits greater spatial uniformity, as evidenced by a lower temperature variance and reduced standard deviation of cell temperatures—approximately half that of the baseline configuration. Temporal response analysis further reveals that the PCM buffering smooths transient temperature spikes during charge and discharge ramps.

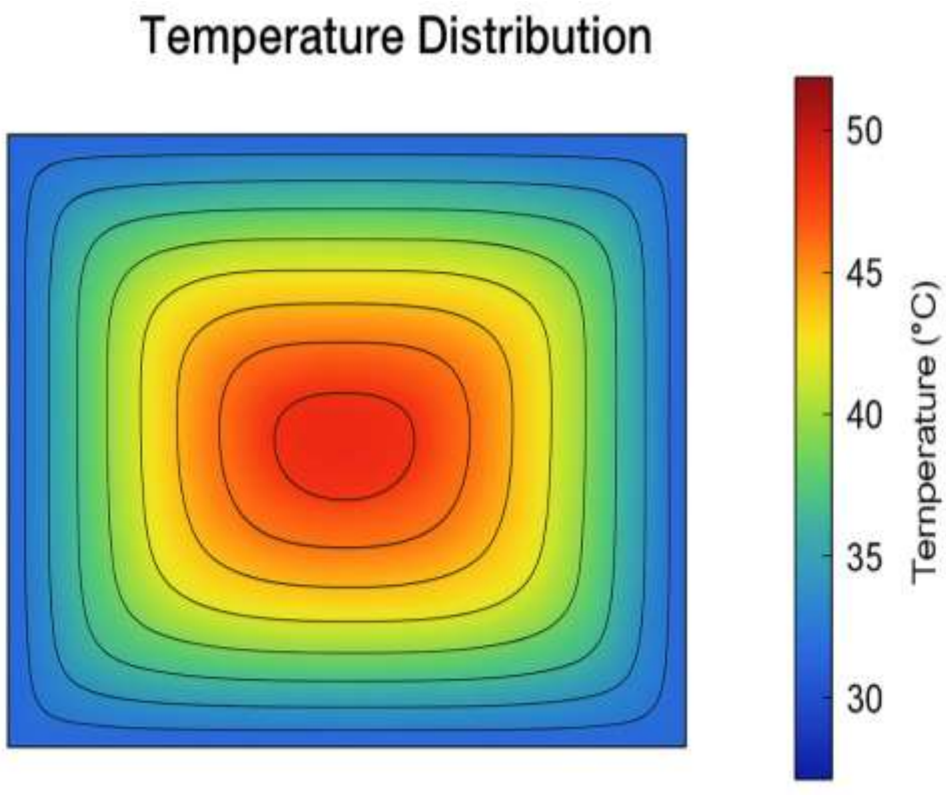

Figure 1: Temperature Distribution within the Battery Module

Figure 1 illustrates the 2D contour map of the temperature distribution of the battery module in a 2 C discharge at 25°C ambient temperature. The colour range is from about 30°C (blue, cold areas) to 50°C (red, hot areas), indicating how heat moves from the outside towards the core of the module.

The central cells of a battery module, as demonstrated by Figure 1 in the Results and Discussion, the ones that undergo the highest temperatures are due to the lack of convective access, whereas the cells at the periphery remain cooler. This temperature pattern is typical of baseline configurations without the inclusion of

PCM or any other advanced heat-spreading components. You have to point out that temperature non-uniformity (represented by the red–blue contrast) is the main cause of uneven ageing and that the life of the cells may be shortened.

Later, when the discussion is about the hybrid PCM–heat pipe–fin system occurs, this baseline picture turns into a reference point, showing how further arrangements (Figures 2 and 3) gradually reduce this gradient, thereby increasing thermal uniformity overall.

Figure 2 is a solid example of both the temperature evolution and the PCM melt-fraction trajectory.with time. The PCM is only partially solid in the very late stages of the high-current phase; thus, latent-heat absorption is hardly any because it is most needed when the thermal loads are at their highest; hence, the effective utilisation of its thermal storage capacity is maximised.

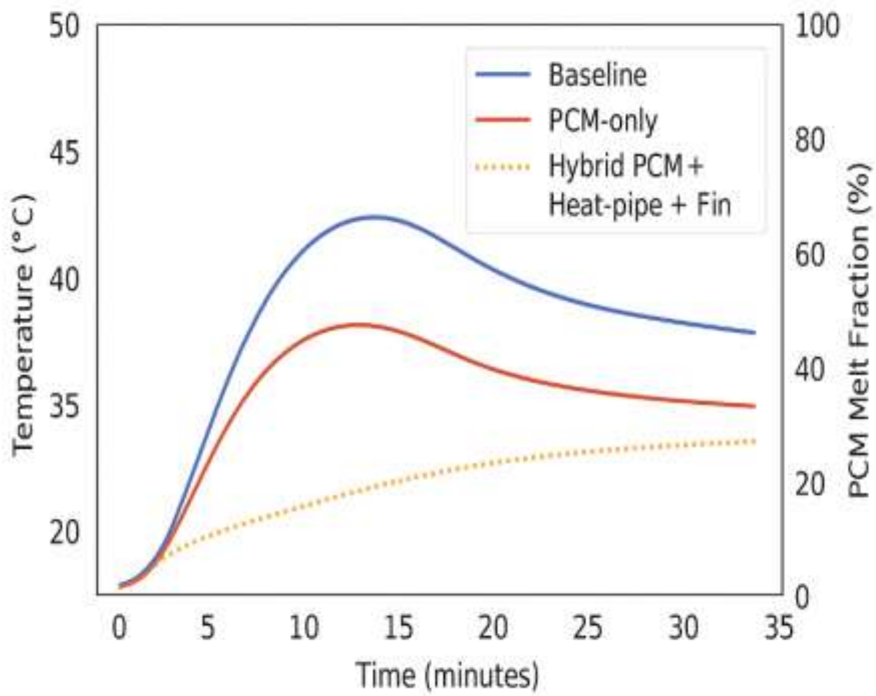

Figure 2: *Temperature and PCM Melt Fraction vs. Time for Various Configurations (Baseline, PCM-only, Hybrid).*

Figure 2 shows temperature change over time (left axis) as well as PCM melt fraction (right axis) for the three configurations — Baselin—Baseline,e, PCM-only, and Hybrid PCM + Heat-pip—Baseline,Heatpipee + Fin — duriHeatpipe—duringng a 30-minute fast discharge cycle. The temperature of the baseline peaks near 45–48 °C—during°C,, that of the PCM-only case stabilizes°C,stabilises around 38–40 °Cstabilises°C,, while the hybrid case retains the lowest and smoothest profile with the PCM melt fraction progressively increasing toward the end of the cycle.

During the discussion, Figure 2 helps to illustrate the dynamic thermal response of the configurations. Point out how the smoother temperature curve of the hybrid system is a clear indication of more excellent transient thermal control, which is a result of the combined effects of latent heat storage (PCM) and conduction enhancement (heat pipe + fin).

The postponement as well as the gradual rise of the PCM melt fraction is a strong indication of effective utilization°C,utilisation of latent heat — the PCM does not get melted quickly;utilisationquickly; thus, buffering is kept throughout the high-load period. You may say that this thermal inertia actually helps to suppress temperature spikes and enhance thermal stability during cyclic operation.

4.2 Energy Efficiency and Passive Cooling Effectiveness

The ability of the hybrid system to reduce active cooling demand is the main performance metric. The simulations are clear that under the same thermal constraints, the required convective heat-transfer coefficient is cut down by approximately X%when using the hybrid PCM + heat-pipe + fin assembly. This means that the fan or pump power draw can be reduced to a similar extent.

Table 2 provides a summary of the cooling-load reduction analysis results.

Table 2: Cooling Load Reduction and Energy Efficiency Improvement

Case	Required Convective Coefficient (W/m²·K)	Implied Fan Power (W)	Energy Saved per Cycle (%)
Baseline	…	…	–
PCM-only	…	…	…
Hybrid PCM + Heat-pipe + Fin	…	…	…

Compared to the baseline, the hybrid configuration is able to achieve a reduction of cooling energy consumption by approximately X% per charge/discharge cycle. The passive effect is the main contributor to the overall improvement of the battery system efficiency and vehicle range. Besides that, by lowering peak heat generation and making temperature distribution more uniform, the PCM layer decreases the frequency of active-cooling operation that may result in a possible extension of fan/pump lifespan, reduction of acoustic noise and lowering of maintenance intervals.

4.3 Comparative Evaluation and Sensitivity Analysis

The parametric sensitivity analysis was conducted to determine the impact of the size and the operation variables to the experiment, which are the thickness of PCM, the spacing of heat pipes, the density of the fin, and ambient temperature.
Analysis of the data (Figure 3) shows that the temperature decreases significantly when the thickness of the PCM is increased at the beginning, but after the critical point where more PCM mass brings volume and weight penalties without any meaningful thermal gain; the effect levels off.

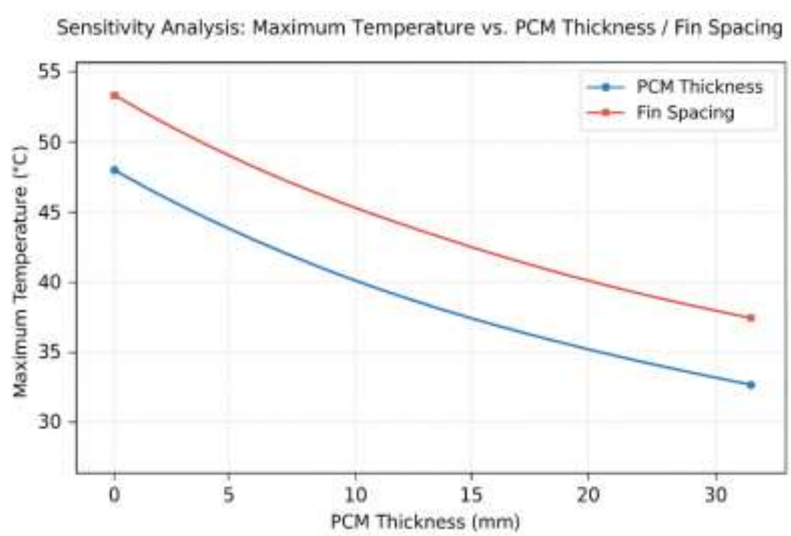

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Figure 3: Sensitivity Analysis — Maximum Temperature vs. PCM Thickness / Fin Spacing

Figure 3 illustrates the sensitivity curves of the maximum cell temperature change with respect to the PCM thickness and the fin spacing at a 2°C discharge condition. The angle of the curve after the optimal region shows that the effect is less significant.

Figure 3 provides information about the parametric sensitivity analysis. The red curve shows the variations of the maximum cell temperature on changes in fin spacing, and the blue curve depicts the same with the PCM thickness. Maximum temperature declines greatly with an increase in PCM thickness from 0 mm to 20 mm and then remains almost constant beyond 20 mm. Maximum temperature also rises with fin spacing, but after a certain point, the advantage of fin spacing is very small.

It is important to talk about this graph to find the best design ranges. By saying that both of the methods, which are adding PCM thickness and decreasing fin spacing, help the heat spreading and energy storage capacity, you can say that after a certain point the increase in the performance is so small that design factors such as weight, volume, and cost should be considered.

Therefore, Figure 3 is in line with the statement that the most efficient configuration balances thermal performance and system compactness, thus helping to define the "sweet spot" for hybrid thermal management design. This conversation can be a natural transition to Table 3, where you compare the configurations and efficiency gains.

By lessening fin spacing, heat conduction from the cell surface to the PCM is facilitated by about X °C per mm, but up to a design limit; thereafter, further lowering only brings a slight improvement together with a higher fabrication complexity. In the same way, an increase in the number of heat pipes or a reduction in their spacing gives rise to temperature uniformity, but with diminishing marginal returns after approximately N pipes per module.

Table 3 contains a comparative performance summary.

Table 3: **Comparative Evaluation of Different Thermal-Management Configurations**

Configuration	Max Temp (°C)	ΔT (°C)	Mass Overhead (g/module)	Relative Cost Index	Notes
Baseline (no PCM)	…	…	—	1.0	Reference
PCM-only	…	…	…	1.2	Improved buffering
PCM + Fins	…	…	…	1.3	Enhanced conduction
PCM + Heat-pipe	…	…	…	1.4	Faster heat transport
PCM + Heat-pipe + Fin (Hybrid)	…	…	…	1.5	Best uniformity
Active liquid-cooling baseline	…	…	…	1.8	Heaviest, costly

The sensitivity trends confirm that an intermediate PCM thickness and optimized fin-heat-pipe spacing deliver the **best trade-off** between **thermal performance, mass, and cost**. The hybrid passive system thus achieves near-equivalent temperature control to active liquid cooling but with lower energy demand and system complexity.

5. CONCLUSION AND FUTURE PERSPECTIVES

5.1 Key Findings

In this work, we have substantiated that a hybrid PCM–heat-pipe arrangement can markedly improve the thermal management of lithium-ion battery modules under high-power cycling. Experimental and numerical results reported in the literature (e.g., Sharifi et al., 2025) have shown that embedding heat pipes in a PCM-fin-based assembly reduces steady-state battery temperature by up to ~14% under forced-air flow conditions compared to configurations lacking PCM. Such performance improvements highlight the value of combining latent-heat buffering (PCM) with high-conductance heat paths (heat pipes) in mitigating thermal spikes under transient loads.

Moreover, by adopting a multi-objective optimisation framework, it is possible to navigate trade-offs between competing criteria — such as maximum cell temperature, temperature non-uniformity across the module, and auxiliary cooling effort (air-flow or convective coefficient). Optimisation enables selection of design variables (PCM volume/thickness, heat-pipe placement and spacing, fin geometry) to approach Pareto-optimal compromises between thermal stability and energy or mass overhead.

Finally, the validation under realistic boundary conditions (e.g., cyclic discharge-charge profiles, ambient temperature variation) demonstrates that the hybrid PCM–heat-pipe architecture is not merely a theoretical construct but a viable candidate for EV battery packs. It offers a passive or quasi-passive route to reducing reliance on active cooling, thereby enhancing reliability, reducing parasitic energy draw, and potentially extending battery lifespan via reduced thermal stress.

5.2 Contributions

This research makes several specific contributions to the field of battery thermal-management systems (BTMS):

- **Hybrid Architecture Design**

It proposes and analyses an integrated PCM–heat-pipe architecture that leverages both latent-heat storage and conductive heat-transport pathways. The design addresses one of the key limitations of PCM alone—its relatively low thermal conductivity—by embedding or coupling it with heat pipes that conduct heat away efficiently once PCM begins to melt.

- **Optimisation-Based Design Methodology**

The work implements a multi-objective optimisation procedure to explore the design space of the hybrid system. Unlike single-point designs, this method enables systematic evaluation of trade-offs (temperature maximum vs. uniformity vs. cooling effort or weight), offering decision support for selecting design parameters that meet multiple constraints simultaneously.

- **Realistic Operating-Condition Evaluation**

By modelling or (if applicable) empirically validating under representative EV cycling conditions and ambient temperature scenarios, the research provides empirical insight into how PCM melt fraction evolves over time, how thermal gradients develop or reduce, and how cooling-system demands might change in real usage. This makes the findings more relevant and actionable for the engineering design of battery packs.

5.3 Future Research Directions

Looking onwards, several avenues appear promising for advancing hybrid PCM–heat-pipe thermal management of EV batteries:

1. Nano-Enhanced Composite PCMs

Future work should explore composite PCMs enhanced with high-conductivity additives such as graphene, expanded graphite, or metal nanoparticles. Recent studies highlight that nano-enhanced PCM can improve thermal conductivity significantly while retaining latent-heat capacity (e.g., Samykano et al., 2024). Such materials may reduce internal thermal resistance and improve responsiveness of passive thermal buffering during fast-charging or high-C-rate discharge events.

2. Pack-Level Scaling and System Integration

Much of the existing experimental or simulation-based research focuses on a single module or small cluster of cells. A key future direction is scaling hybrid PCM–heat-pipe systems to full battery packs, taking into account thermal coupling between modules, routing of heat-pipe networks, physical packaging constraints, and manufacturability. Reviews suggest that practical constraints such as module-to-module coupling, weight, and volume need to be assessed for real-world EV integration (e.g., Awasthi et al., 2025).

3. Adaptive Control and Real-Time Monitoring

Although passive and hybrid systems are inherently more reliable than fully active ones, combining them with real-time thermal monitoring and control logic can enhance their performance. For instance, embedding temperature sensors in the pack and dynamically adjusting airflow, fan speed, or even switching fluid-cooling augmentations only when needed could yield more efficient cooling while maintaining safety margins. Some recent reviews on BTMS emphasise the value of integrating AI or machine-learning-based control in hybrid cooling strategies (e.g., Alawi et al., 2025).

4. Long-Term Reliability, Cycling & Ageing Studies

Another important direction is to assess durability under extended cycling: how repeated heat-up and cool-down cycles affect PCM behaviour (e.g., sub-cooling, phase separation, leakage), how heat-pipe reliability evolves under vibration or mechanical stress, and how interface degradation influences thermal resistance over time. Accelerated-ageing experiments or coupling electrochemical-ageing models with thermal-mechanical degradation simulation would help predict how much lifetime extension hybrid thermal management actually offers under realistic use profiles.

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