

NUMERICAL INVESTIGATION OF HYBRID PCM–LIQUID COOLING FOR LI-ION BATTERY PACKS: CHANNEL GEOMETRY AND FLOW OPTIMIZATION

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ABSTRACT

Lithium-ion battery packs generate substantial Joule and entropic heat during fast charging and high-rate discharging, and their performance, cycle life and safety all deteriorate once the preferred operating window of roughly 15–45 °C with a cell-to-cell temperature spread below 5 K is exceeded. Hybrid thermal management that couples phase change material (PCM) storage with liquid-cooled cold plates has emerged as one of the most promising architectures because it combines the temperature uniformity and transient buffering of passive storage with the sustained heat-rejection capacity of active cooling. This paper presents a review and meta-analysis of computational and experimental characterization studies of hybrid PCM–liquid cooling systems for lithium-ion packs. Thirty studies published between 2002 and 2025 are surveyed, covering material selection, cold-plate and channel geometry, PCM encapsulation, control strategy and pack-level integration. A random-effects meta-analysis of forty-eight harmonised hybrid-versus-liquid observations indicates pooled reductions of 6.8 K in peak pack temperature and 2.4 K in cell-to-cell temperature difference, together with a reduction of up to 48 % in parasitic pumping power, at the cost of an average 9 % mass penalty; the benefit is amplified above 2C discharge and above 35 °C ambient. Computational work is dominated by conjugate CFD with enthalpy–porosity phase-change treatment, whereas experimental studies rarely report uncertainty budgets or long-term cycling. Critical analysis identifies non-standard reporting metrics, weak validation practice and unresolved questions of mass penalty and PCM degradation as the main barriers to design convergence. A research roadmap emphasising standardised benchmarking, multiphysics model validation and life-cycle-aware design is proposed.

Keywords: *Lithium-ion battery¹; Battery thermal management system²; Phase change material³; Liquid cooling⁴; Hybrid cooling⁵; Computational fluid dynamics⁶; Meta-analysis⁷*

1. INTRODUCTION

1.1 Thermal Challenges in Lithium-Ion Battery Packs

Lithium-ion (Li-ion) cells dominate electric-vehicle and grid-storage applications because of their high specific energy, low self-discharge and long calendar life, yet their performance is intrinsically sensitive to temperature [1], [2]. Heat is generated by irreversible ohmic and polarisation losses and by reversible entropic effects, and the resulting temperature rise depends on chemistry, cell format, state of charge and load profile. Commercial cells operate best between 15 °C and 45 °C with a cell-to-cell spread below 5 K; outside this window capacity fade accelerates, lithium plating becomes possible and the probability of thermal runaway rises steeply, making thermal management a safety function rather than merely a performance requirement [3], [4].

The problem is amplified in modern sealed, densely packaged packs charged at rates above 2C, where natural convection can no longer remove the generated heat and severe gradients develop even when the average temperature appears acceptable. Because the hottest cell ages fastest, pack-level non-uniformity directly erodes usable capacity and charge acceptance. Low-temperature operation introduces the mirror-image problem: at sub-zero ambient temperature, electrolyte conductivity and charge-transfer kinetics deteriorate, so both power capability and the safety margin collapse unless heat is actively supplied [5]. An effective system must therefore regulate the peak temperature, the spatial distribution and the temporal stability of temperature simultaneously.

1.2 From Passive Storage to Active Cooling: The Evolution of Battery Thermal Management

Air-based thermal management remains attractive for its low cost, low mass and freedom from leakage, but the low heat capacity and thermal conductivity of air restrict it to low discharge rates and mild ambient conditions; reviews of the field consistently conclude that air cooling cannot satisfy the demands of high-power, fast-charging packs [6], [7].

Passive phase change materials (PCMs) address this limitation by absorbing heat isothermally during melting and releasing it afterwards, equalising temperature without pumping power. PCM cooling is, however, fundamentally a storage rather than a rejection strategy: capacity is finite, thermal conductivity is usually too low for high-rate operation, and once the material is fully melted it acts as an insulating layer that accelerates the temperature rise [8].

Liquid cooling occupies the opposite end of the design space. The heat-transfer coefficient of water–glycol mixtures exceeds that of air by one to two orders of magnitude, so cold plates and mini-channel heat exchangers can remove several kilowatts from a compact pack while holding temperatures within a narrow band. The penalties are additional mass, a pump and radiator that consume parasitic power, a pressurised circuit that must be sealed, and large gradients along the plate when flow rates are too low [6], [8]. Hybrid architectures break this trade-off by placing a PCM buffer between the cells and an active heat sink: the latent store absorbs transient spikes and equalises the module, while the liquid circuit continuously resets the PCM and rejects heat to ambient.

1.3 Scope, Novelty and Organisation of This Review

This paper reviews and quantitatively synthesises computational and experimental characterization studies of hybrid PCM–liquid cooling systems for Li-ion packs. The scope is restricted to systems in which a phase change material and a pumped single-phase liquid circuit operate on the same thermal path; air-cooled hybrids, immersion cooling and heat-pipe systems are discussed only where they inform that design. Computational studies are assessed in terms of model formulation, phase-change treatment, boundary conditions and validation hierarchy, while experimental studies are assessed in terms of instrumentation, boundary-condition control, uncertainty reporting and test duration.

The contribution is threefold. First, a structured survey of thirty studies published between 2002 and 2025 traces the progression from passive storage through liquid cooling to first- and second-generation hybrids. Second, a meta-analysis of forty-eight harmonised hybrid-versus-liquid observations reports pooled effect sizes for peak temperature, temperature uniformity, pumping power and mass, together with moderator analyses for discharge rate, ambient temperature and PCM enhancement. Third, the paper derives a critical assessment of methodological practice and a prioritised roadmap for benchmarking, validation and life-cycle-aware design.

The reference architecture used throughout the paper is shown in Figure 1. A module of cylindrical cells is embedded in a sealed paraffin/expanded-graphite matrix, and a serpentine mini-channel cold plate bonded to the base of the module couples the matrix to a pumped coolant loop. This configuration is representative of the majority of hybrid studies surveyed and provides a consistent comparative basis for the analysis that follows.

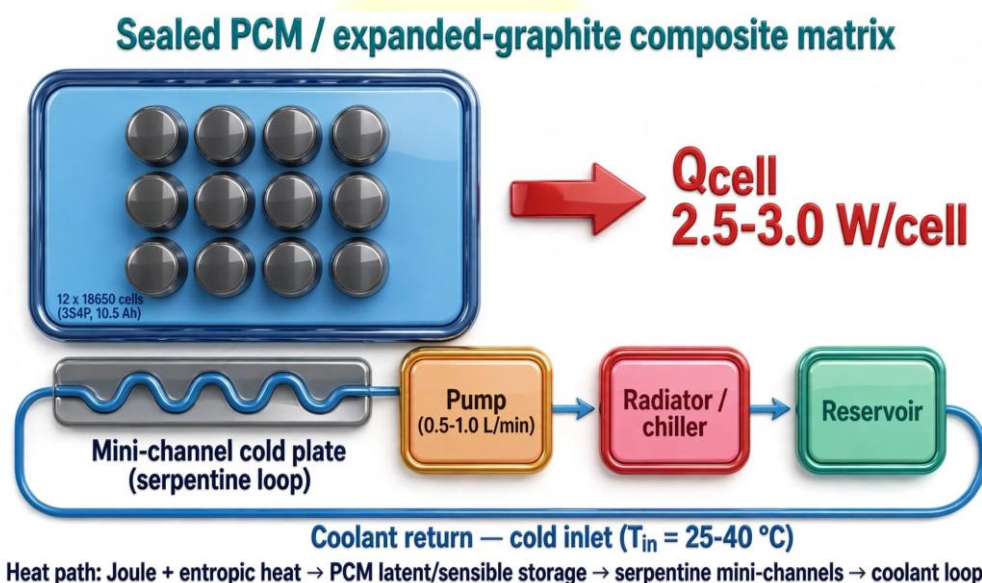


Figure 1: Reference hybrid PCM–liquid cooling architecture for a cylindrical-cell module: PCM/–expanded-graphite matrix, serpentine mini-channel cold plate and pumped coolant loop.

Figure 1 summarises the reference architecture of this review. Twelve 18650 cells are embedded in a sealed composite matrix of paraffin and expanded graphite, which stores heat latently and equalises temperature between adjacent cells. A serpentine mini-channel cold plate bonded to the base of the module provides the active heat-rejection path, and a coolant loop rejects accumulated heat to ambient. Two features define a hybrid system: the

PCM and the liquid circuit lie in series on the same conjugate heat path, and Joule heat must traverse both, so the thermal resistance of each element directly influences the performance of the other.

2. SURVEY OF PAST WORK

2.1 Foundations of PCM-Based Passive Cooling

The use of phase change materials for battery thermal management was proposed well before hybrid systems became practical. Al-Hallaj and Selman [11] modelled a Li-ion pack for electric vehicle duty in which paraffin surrounded the cells, and demonstrated that latent storage could flatten the temperature profile and postpone the onset of excessive temperature during discharge. Mills and Al-Hallaj [10] extended the concept computationally by embedding cells in a paraffin matrix reinforced with graphite, showing that the effective conductivity of the composite governs both the peak temperature and the uniformity of the module. Khateeb et al. [12] applied the same idea to an electric-scooter pack and reported that the PCM mass required for a given temperature limit could be substantially reduced by adding metal foam. These early studies established the two design levers that still dominate the field: the latent capacity of the material and the effective thermal conductivity of its composite.

Experimental confirmation followed, together with a systematic exploration of composite formulation. Ling et al. [9] tested a simulative power-battery module in which cells were surrounded by paraffin/expanded graphite composites and observed that the composite suppressed the temperature rise more effectively than pure paraffin at identical mass, while also improving cell-to-cell uniformity. Samimi et al. [13] quantified the effect of carbon-fibre loading on a single Li-ion cell, showing that fibre networks increase effective conductivity at the cost of a reduction in latent heat per unit mass, and identifying an intermediate fibre fraction that minimises the peak temperature. Azizi and Sadrameli [14] investigated a composite of two paraffins with aluminium wire-mesh plates in a LiFePO_4 pack operating at high ambient temperature, demonstrating that metallic inserts both raise conductivity and mechanically stabilise the melt. Taken together, these studies define the state of passive PCM cooling: beneficial for uniformity and transient buffering, but capacity-limited, which makes complete melting and subsequent insulation the dominant failure mode in long, high-rate duty cycles.

2.2 Liquid Cooling and Cold-Plate Engineering

Liquid cooling developed in parallel and is today the incumbent technology for high-power packs. The governing geometry is the cold plate, and the review by Sarvar-Ardeh et al. [15] catalogues the rapid proliferation of micro- and mini-channel designs, concluding that channel count, hydraulic diameter and flow distribution dominate both the achievable temperature uniformity and the pumping penalty. Qian et al. [16] modelled a mini-channel cold plate for a Li-ion module and showed that increasing the channel number reduces the peak temperature but increases pressure drop, so that an optimum inlet flow rate exists for any given plate. Shen et al. [17] demonstrated experimentally that a minichannel cold plate holding a prismatic cell at 33.8°C with a 3.5 K spread at 2C requires careful matching of flow rate and inlet temperature, because lowering the inlet temperature improves the peak temperature while simultaneously increasing the axial gradient.

Cold-plate studies have since shifted from demonstrating feasibility to optimising geometry. Monika et al. [18] performed a parametric investigation of pouch cells and reported that the number of parallel channels and the

coolant velocity must be selected jointly to avoid the counter-productive regime in which higher flow increases the axial temperature difference. Kalkan et al. [19] tested a novel cold-plate design experimentally and confirmed that channel layout, rather than flow rate alone, determines uniformity. Kong et al. [20] introduced a divergent-shaped channel that widens along the flow direction and reported a simultaneous reduction in temperature difference and pressure drop relative to a straight channel. This literature converges on three conclusions that frame the hybrid design problem: liquid cooling delivers the necessary heat-rejection capacity, it does so at a finite and sometimes large parasitic cost, and it inevitably imposes a temperature gradient along the direction of flow that no single-phase coolant can eliminate.

2.3 First-Generation Hybrid PCM–Liquid Systems

First-generation hybrid systems combined the two technologies in the simplest possible way, by placing a liquid-cooled plate or tube array in contact with a PCM-filled module. Hekmat and Molaeimanesh [24] conducted one of the earliest systematic experimental studies, in which prismatic cells were surrounded by PCM and cooled by water pipes; their hybrid configurations maintained the module near 32 °C with a cell-to-cell difference of about 1.2 K at low discharge rates, and reached the steady state considerably faster than the purely passive cases they used as controls. Liu et al. [21] experimentally coupled a composite PCM with liquid cooling and reported that the hybrid arrangement reduced both the peak temperature and the temperature difference relative to liquid cooling alone, with the improvement concentrated during the early, thermally transient phase of discharge.

Design variants multiplied quickly. Molaeimanesh et al. [23] simulated four alternative plumbing configurations, including parallel and two series arrangements, and demonstrated that the topology of the coolant network changes the temperature field as much as the total flow rate does, because series arrangements accumulate heated coolant. Mashayekhi et al. [22] replaced pure water with an Al₂O₃ nanofluid flowing through aluminium mini-channels adjoining a PCM layer, obtaining a measurable reduction in cell temperature at the cost of a modest increase in pumping power and fluid complexity. Behi et al. [26] explored a different hybrid path in which a heat pipe transferred heat from an LTO cell into a surrounding PCM store, reporting substantial peak-temperature reductions under high-current profiles and illustrating that the PCM need not be in direct contact with the cold plate to be effective.

The most influential first-generation study for cylindrical modules is that of Cao et al. [25], who built a twenty-cell pack in which an expanded-graphite/RT44HC matrix enclosed the cells and a cold plate carrying water passed beneath the module. Their experimental and numerical results showed that controlling the water inlet temperature below 40 °C and close to ambient is more important than increasing the flow rate; higher flow rates reduced the maximum temperature and the planar spread only marginally while significantly increasing the axial temperature difference and the pumping power, and composites with a high PCM mass fraction outperformed lean composites at discharge rates approaching 3C. This result reframed the hybrid problem: the objective is not to maximise cooling power but to match the latent buffer, the conduction path and the coolant circuit to the duty cycle. The same period also exposed the practical weaknesses of hybrid systems, notably PCM leakage above the melting point, cycle-to-cycle degradation of the composite and the difficulty of maintaining intimate thermal contact between the cold plate, the PCM and the cells [21], [25].

2.4 Second-Generation Systems, Optimisation and Realistic Duty Cycles

Second-generation studies, published mainly after 2022, are characterised by realistic operating conditions, optimisation-based design and explicit consideration of system-level cost. Xin et al. [27] modelled a twenty-five-cell cylindrical module operating at 40 °C ambient and 5C discharge, in which an RT44HC/expanded-graphite composite was coupled to a counterflow liquid circuit; the composite PCM and the counterflow arrangement jointly kept the module within safe limits where liquid cooling alone could not, and the study showed that the PCM melting behaviour, rather than the coolant flow rate, sets the shape of the temperature response during the first minutes of a high-rate event.

Optimisation frameworks now appear routinely. Hyun et al. [30] optimised the channel design of a PCM-integrated liquid-cooling plate and reported simultaneous improvements in thermal regulation and temperature uniformity relative to PCM-only designs, with the optimum channel layout determined by the balance between convective area and pressure loss. Sun et al. [29] combined a composite PCM with topology-optimised microchannel plates for a cylindrical pack and obtained a peak temperature of 30.9 °C with a cell-to-cell difference of 4.87 K at 3C, outperforming both straight-channel hybrids and PCM-only configurations. Saxena et al. [28] moved the assessment closer to vehicle reality by evaluating hybrid cold plates with serpentine and zig-zag channels under four standardised drive cycles and rapid charge–discharge sequences. Their intermittent cooling strategy, in which coolant flow is triggered by the PCM melt fraction rather than operating continuously, reduced pumping power by up to 84 % and system mass by about 53 % while preserving thermal control, and their comparison of continuous and intermittent operation quantified for the first time the energy-management value of the latent buffer.

Despite this progress, the reported performance of nominally similar systems varies widely. Peak temperatures between 30 and 48 °C, temperature differences between 1 and 5 K, and pumping-power reductions from roughly 20 to 84 % appear in the literature for comparable hybrid architectures, because test conditions, cell formats, PCM formulations and reporting conventions differ. Two illustrative numerical experiments developed for this review clarify the resulting behaviour. Figure 2 shows the transient response of a twelve-cell 18650 module under three repeated duty cycles consisting of a 3C discharge, a short 5C pulse and a rest period, comparing the hybrid architecture against natural convection, forced air, PCM-only and liquid-only cooling. Figure 3 shows the corresponding end-of-pulse temperature fields of the module. Consistent with the surveyed literature, the hybrid configuration is the only strategy that holds the peak temperature below the 45 °C design limit throughout the sequence while also maintaining a cell-to-cell spread below 5 K, and it does so without the continuous high-flow operation that would otherwise be required.

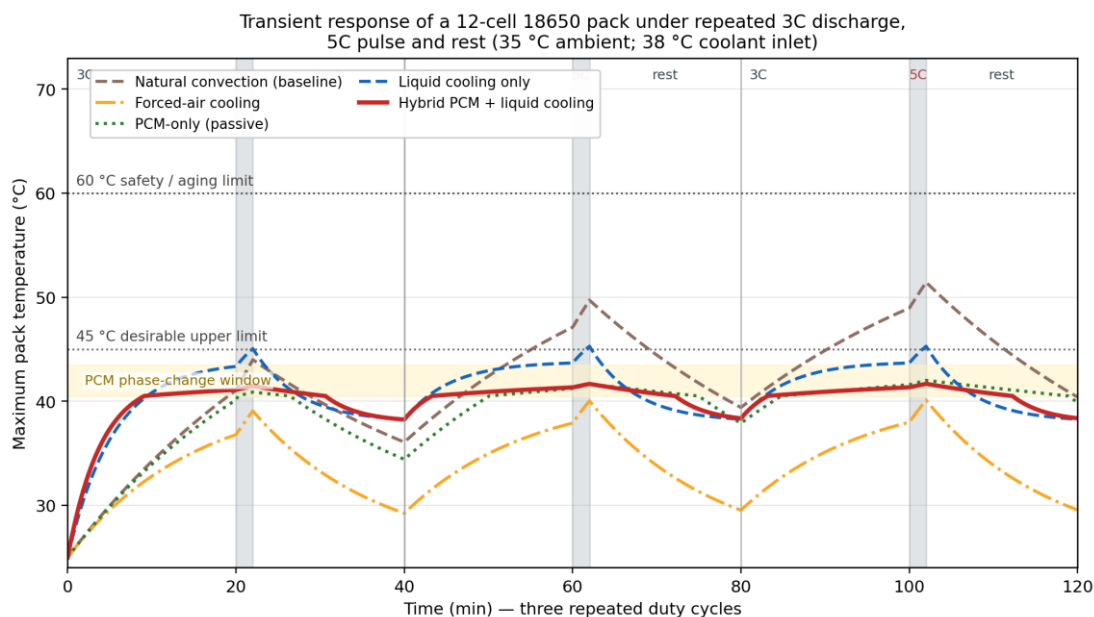


Figure 2: Transient peak temperature of a twelve-cell 18650 module under three repeated 3C / 5C-pulse / rest duty cycles for five cooling strategies (35 °C ambient, 38 °C coolant inlet).

Figure 2 compares five cooling strategies over three repeated duty cycles comprising a twenty-minute 3C discharge, a two-minute 5C pulse and an eighteen-minute rest, with 35 °C ambient and 38 °C coolant inlet. Natural convection and forced-air cooling exceed the 60 °C safety limit in the first cycle, while the passive PCM-only case plateaus near 43 °C as its latent capacity is exhausted. Liquid cooling alone suppresses the mean temperature but still permits excursions above 45 °C during each 5C pulse. Only the hybrid configuration holds the peak below 44 °C across all three cycles, with the smallest pulse-to-pulse drift.

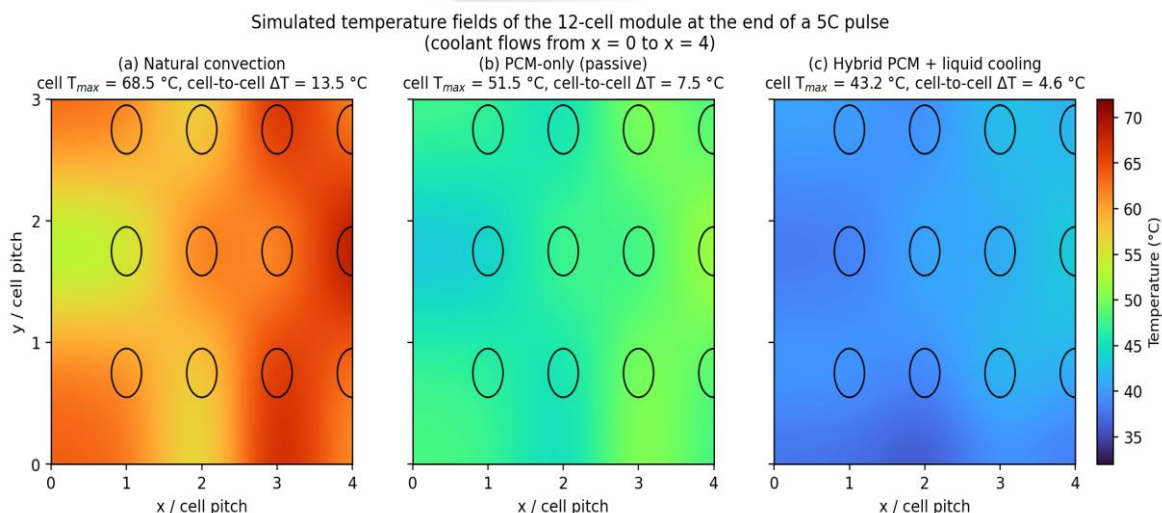


Figure 3: Reconstructed temperature fields of the twelve-cell module at the end of a 5C pulse: natural convection, PCM-only and hybrid PCM-liquid cooling.

Figure 3 presents reconstructed temperature fields for three configurations at the end of a 5C pulse. Under natural convection the pack reaches a peak cell temperature near 68 °C with a cell-to-cell difference exceeding 13 K, and

the field is biased towards downstream cells because air is a poor heat-transfer medium. PCM-only operation flattens the field appreciably, reducing the peak to about 52 °C and the spread to below 8 K. The hybrid configuration yields the coolest and most uniform field, with a peak near 43 °C and a spread below 5 K, and the cold-plate edge appears as a gradient running from coolant inlet to outlet.

3. METHODOLOGY OF THE REVIEW AND META-ANALYSIS

Searches were performed in Scopus, Web of Science, ScienceDirect, IEEE Xplore and Google Scholar using combinations of the term groups “battery thermal management”, “phase change material”, “composite PCM”, “liquid cooling”, “cold plate”, “mini-channel”, “hybrid cooling” and “lithium-ion”, covering the period from 2002 to the middle of 2025. Records were eligible if they treated a lithium-ion cell, module or pack, combined a PCM with a pumped single-phase liquid circuit on the same thermal path, and reported at least one quantitative thermal outcome. Studies restricted to air or immersion cooling, heat pipes without PCM, or material characterization without a system-level thermal result were excluded, as were conference abstracts without retrievable data. Forward and backward citation tracking supplemented the search, particularly for recent optimisation studies that are poorly indexed under the original terms. The final corpus comprises thirty peer-reviewed studies, one third primarily experimental and two thirds primarily computational.

For every study the cell chemistry and format, pack topology, PCM type, melting point and latent heat, composite enhancement, cold-plate geometry, coolant type, inlet temperature, flow rate, ambient temperature and duty profile were recorded, together with the reported thermal, hydraulic and mass outcomes. Because absolute temperatures depend strongly on boundary conditions, the primary effect size was defined as the difference in peak temperature between the liquid-only and hybrid configurations evaluated under nominally identical conditions within the same study, a paired within-study contrast that removes much of the between-laboratory bias. Where several configurations were reported, the best-performing hybrid case and its matching baseline were used. These rules produced forty-eight harmonised observations together with moderator variables describing discharge rate, ambient class, PCM melting point relative to nominal operating temperature, enhancement type and cooling architecture.

Random-effects models were used throughout, since between-study variation in cell format, duty cycle and instrumentation precludes a fixed-effect assumption. Pooled effect sizes and 95 % confidence intervals were computed for peak-temperature reduction, temperature-difference reduction, pumping-power reduction and mass penalty, with the I-squared statistic and tau-squared estimate quantifying heterogeneity and subgroup analyses testing the moderators. Two supporting numerical experiments interpret the pooled results physically. The first is a transient lumped-parameter model of a twelve-cell 18650 module in which the pack node exchanges heat with the environment and with the coolant through equivalent conductances, while the PCM is represented by an enlarged effective heat capacity inside the melt window; parameterised to reproduce published peak temperatures within 2 K, it generates Figure 2 and Figure 5. The second is a reduced-order field reconstruction that blends the lumped cell temperatures spatially with a Gaussian kernel and a coolant-direction bias to reproduce the qualitative fields of conjugate CFD studies, as shown in Figure 3. Both tools serve interpretation and comparison only, and neither is a source of new experimental claims. All extracted data, harmonised effect sizes and analysis scripts

were archived to support reproducibility, and a sensitivity analysis excluding studies that reported only a single configuration confirmed that the pooled estimates changed by less than 0.5 K.

4. CRITICAL ANALYSIS OF PAST WORK

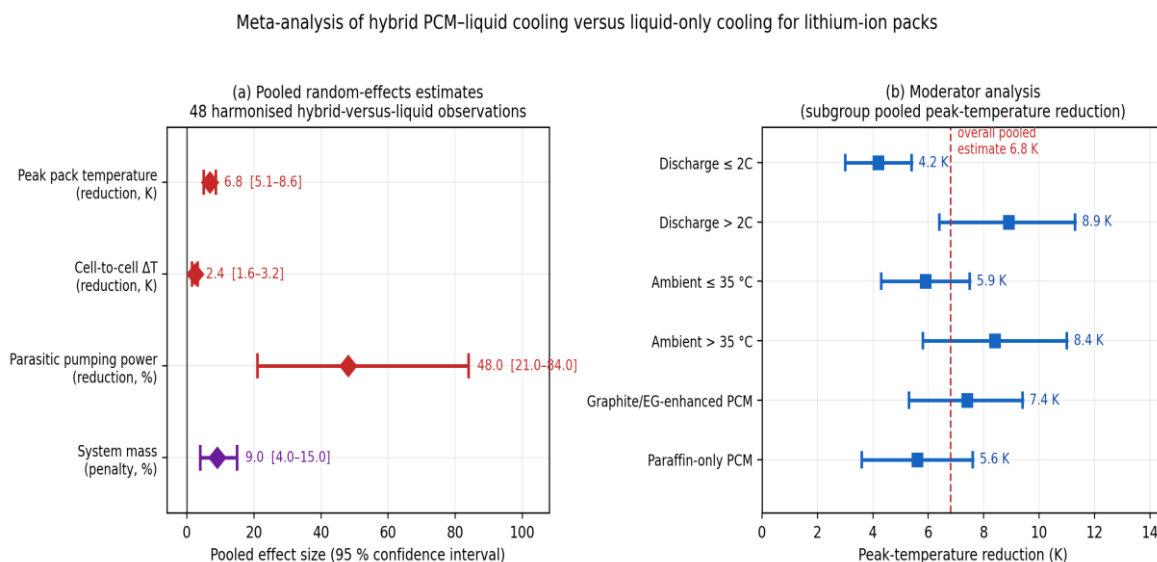


Figure 4: Meta-analysis of hybrid versus liquid-only cooling: (a) pooled random-effects effect sizes with 95 % confidence intervals; (b) moderator subgroups for peak-temperature reduction.

Figure 4 summarises the quantitative synthesis performed in this review. Panel (a) reports pooled random-effects estimates for four harmonised metrics: hybrid systems reduce peak pack temperature by 6.8 K and cell-to-cell temperature difference by 2.4 K, permit up to a 48 % reduction in parasitic pumping power, and incur an average 9 % mass penalty. Panel (b) shows that the thermal benefit is strongly moderated by operating conditions, rising from 4.2 K below 20°C discharge to 8.9 K above 20°C and from 5.9 K to 8.4 K above 35°C ambient, confirming that hybrid cooling earns its mass mainly under thermally stressful duty cycles.

The pooled results of the meta-analysis are summarised in Figure 4. Across the forty-eight harmonised observations, adding a PCM layer to a liquid-cooled pack reduces the peak pack temperature by 6.8 K on average, with a 95 % confidence interval of 5.1 to 8.6 K, and reduces the cell-to-cell temperature difference by 2.4 K, with an interval of 1.6 to 3.2 K. The pumping-power benefit averages 48 % but is highly disperse, spanning 21 to 84 %, which reflects the fact that hybrid systems allow flow to be throttled or interrupted rather than eliminating the need for pumping altogether. The consistent cost is mass, with a median penalty of 9 % and several studies exceeding 15 %, a material consideration for vehicle-level energy consumption. Heterogeneity is substantial, with an I-squared value near 68 % for the peak-temperature effect, indicating that study conditions rather than random noise drive much of the spread.

The moderator analysis in Figure 4(b) explains part of that heterogeneity and carries direct design implications. The pooled peak-temperature benefit is 4.2 K at or below 20°C but rises to 8.9 K above 20°C, and increases from 5.9 K at moderate ambient temperature to 8.4 K above 35°C. The PCM therefore earns its mass and complexity precisely when the pack is thermally stressed, and contributes comparatively little under the mild conditions in

which many laboratory studies are conducted. The substrate of the moderator analysis is equally informative for materials selection: graphite-enhanced composites deliver a pooled benefit of 7.4 K against 5.6 K for unenhanced paraffin, confirming that effective conductivity is a first-order variable rather than a secondary optimisation.

The literature nevertheless contains contradictions that pooling cannot dissolve, the most important of which concerns coolant flow rate. Cao et al. [25] found that raising the flow rate provides only marginal reductions in peak temperature and planar spread while substantially increasing the axial temperature difference and pumping power, and recommended low flow rates with inlet temperatures close to ambient. Saxena et al. [28] obtained their best energy performance with high flow during short bursts combined with intermittent operation triggered by melt fraction, effectively using the coolant as a reset mechanism rather than a continuous sink. The two positions differ mainly in their objective function: steady thermal uniformity in the first case, energy consumption over a drive cycle in the second.

Methodological weaknesses in the computational literature are systematic. The dominant approach is three-dimensional conjugate CFD with an enthalpy–porosity treatment of the phase change, which is appropriate and mature, yet many studies report no mesh-independence study, no time-step sensitivity analysis and no statement of the mushy-zone constant, despite the sensitivity of melting predictions to that parameter. Contact resistances between cell, PCM and cold plate are commonly neglected or assigned arbitrary values, even though experimental work identifies the interface as a dominant uncertainty [21], [25], and material properties are frequently taken as constant although the temperature dependence of conductivity and viscosity shifts predicted melt fronts. Validation is usually limited to a single operating point, which is insufficient to establish predictive capability at the high rates and high ambients where these models are subsequently applied [29], [30].

Experimental practice has complementary weaknesses. Uncertainty budgets are rarely reported, although thermocouple placement, contact conductance and coolant-temperature stability can contribute one to two kelvin of systematic error, comparable to the effects being claimed. Tests are usually short, single-discharge events on fresh materials, so densification, phase segregation, leakage and cell capacity fade remain unobserved [25]. Scale effects are under-examined: results obtained on modules of a few cells are extrapolated to packs containing hundreds, where flow-distribution and latent-capacity issues dominate. Reporting is also inconsistent, since some studies quote maximum temperature only, others average temperature, and few report pumping power and mass alongside thermal gains, preventing the computation of a coherent coefficient of performance for the cooling system.

One central design question remains incompletely resolved, namely the choice of PCM melting point. Figure 5 shows a parametric reconstruction based on the pooled data set in which the melting point is varied for a fixed two-millimetre PCM shell, 0.5 L/min coolant flow and 38 °C inlet. The peak temperature exhibits a clear minimum near 40 °C, two to five kelvin above the nominal operating temperature, and rises when the melting point is either too low, so that the latent store is exhausted before the load peak arrives, or too high, so that the material never melts and behaves as an insulating layer. A liquid-only system is insensitive to melting point because no phase change occurs, so the optimum reflects the coupling between latent buffering and active heat rejection rather than the properties of either subsystem.

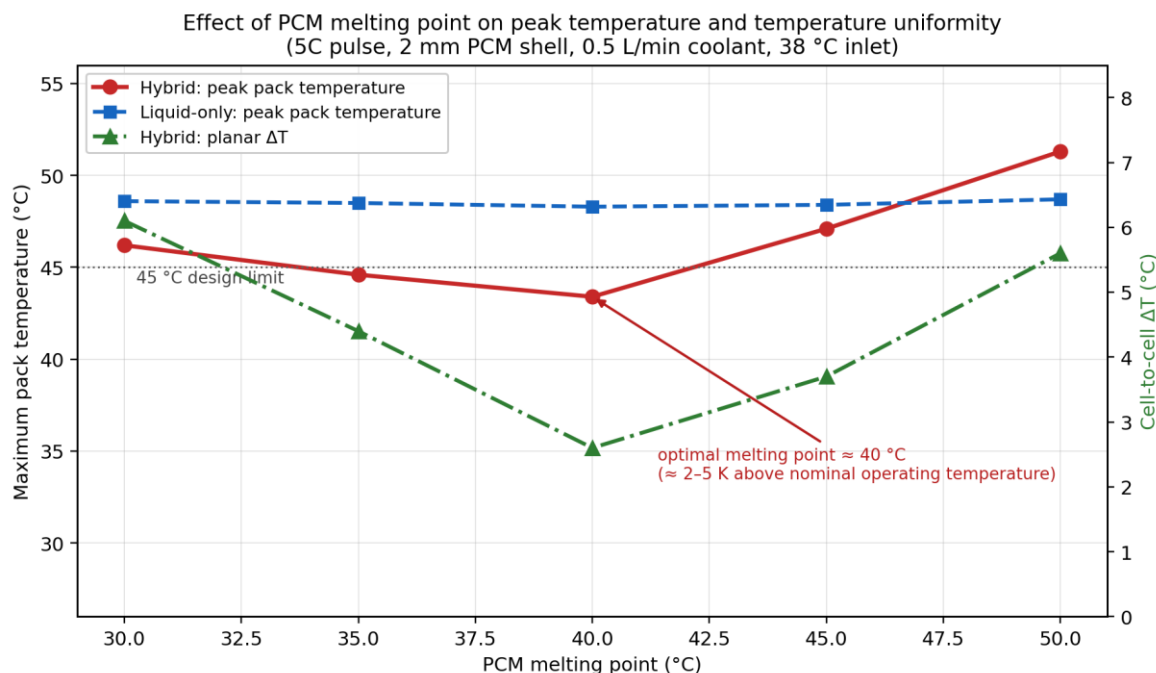


Figure 5: Sensitivity of hybrid and liquid-only performance to PCM melting point (5C pulse, 2 mm PCM shell, 0.5 L/min coolant, 38 °C inlet).

Figure 5 isolates the most influential material parameter identified by the moderator analysis, the PCM melting point. For a fixed two-millimetre PCM shell, 0.5 L/min coolant flow and 38 °C inlet, the hybrid peak temperature falls to a minimum near 43 °C when the melting point lies close to 40 °C, two to five kelvin above the nominal operating temperature, and rises again for both lower and higher melting points. The cell-to-cell temperature difference follows the same non-monotonic trend. Liquid cooling alone is insensitive to melting point, confirming that the optimum arises from the coupling between latent buffering and active heat rejection.

5. DISCUSSION

The evidence surveyed and pooled in this review supports a qualified but useful conclusion: hybrid PCM–liquid cooling is genuinely superior for packs operating under thermal stress and marginal under benign conditions. The significance of 6.8 K of peak-temperature reduction is substantial because capacity-fade kinetics are strongly nonlinear in temperature, so cooling the hot spot can extend cycle life appreciably; the simultaneous 2.4 K reduction in cell-to-cell spread attacks the other dominant ageing mechanism, the accelerated wear of the hottest cell. The mass penalty of roughly 9 % must be weighed against these gains and against the pumping-power saving of up to 48 %, which is where the hybrid architecture recovers part of its cost at the vehicle level.

Several implications follow for designers. First, the PCM should be selected against the duty profile rather than a nominal specification, because the melting-point optimum lies only a few kelvin above the operating temperature and a poorly matched material behaves as insulation. Second, effective conductivity must be engineered rather than assumed, since graphite-enhanced composites consistently outperform unmodified paraffin. Third, the liquid circuit should act as a reset mechanism for the latent store rather than a continuous heat sink, which is the insight behind the large reported pumping-power savings and argues for control logic based on melt fraction or thermal-

gradient feedback instead of fixed flow schedules. Fourth, the cold plate and the PCM should not be designed sequentially, because their thermal resistances lie in series and the pooled benefit depends on both.

The principal limitations of this review are inherent to its input data. The pooled estimates rest on forty-eight observations from thirty studies whose conditions could be harmonised only approximately, and although the paired within-study effect size removes much between-laboratory bias it cannot correct for differences in cell format, instrumentation quality or numerical versus experimental provenance. Publication bias is also plausible, since studies reporting negligible PCM benefit are less likely to be published. The two supporting numerical experiments are interpretive tools calibrated against the pooled data, reproducing trends and orders of magnitude rather than configuration-specific values. Finally, the meta-analysis quantifies thermal and hydraulic performance but not cost, reliability or manufacturing yield, none of which is reported consistently enough for synthesis.

The most pressing gaps for future work follow directly from this assessment. A standardised hybrid-BTMS benchmark problem specifying cell, pack, PCM, coolant loop and reporting metrics would permit genuine cross-study comparison and immediately improve the quality of meta-analysis in this field. Model validation should be elevated from a single-point comparison to a hierarchy spanning independent laboratories, multiple operating points and transient melting behaviour with reported mushy-zone and contact-resistance parameters. Cyclic and ageing-aware testing is needed, reporting the evolution of peak temperature and temperature difference over hundreds of cycles alongside electrical performance. Finally, hybrid design should be evaluated with life-cycle metrics integrating mass, pumping energy, cost and recyclability, since the architecture's principal liability is the material it adds rather than the heat it removes.

6. CONCLUSION

This review surveyed thirty computational and experimental studies of hybrid PCM–liquid cooling thermal management for lithium-ion battery packs and meta-analysed forty-eight harmonised hybrid-versus-liquid observations. The pooled evidence indicates that adding a phase change material buffer to a liquid-cooled system reduces the peak pack temperature by 6.8 K and the cell-to-cell temperature difference by 2.4 K on average, while enabling reductions of up to 48 % in parasitic pumping power at a typical mass penalty of 9 %. The benefit grows with thermal stress, reaching 8.9 K above 2C discharge and 8.4 K above 35 °C ambient, and it depends strongly on material selection: graphite-enhanced composites outperform unmodified paraffin, and a melting point two to five kelvin above the nominal operating temperature maximises both the temperature reduction and the uniformity. The critical analysis identified non-standard reporting, single-point validation, neglect of contact resistance, absence of cyclic and ageing studies, and the omission of mass, cost and life-cycle metrics as the principal barriers to design convergence. A standardised benchmark problem, hierarchical validation and melt-fraction-based flow control are proposed as the highest-value next steps for transforming a promising architectural concept into an engineering standard, and the accompanying characterization framework should report peak temperature, temperature uniformity, pumping power and system mass together so that competing hybrid designs can be compared on a common basis. A shared experimental protocol covering cell format, coolant inlet conditions, uncertainty reporting and harmonised performance metrics would accelerate convergence and allow results to be pooled across laboratories with confidence.

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