

EXPERIMENTAL THERMAL CHARACTERIZATION OF HYBRID PCM–LIQUID COOLING FOR LI-ION BATTERY PACKS UNDER FAST CHARGING AND CYCLIC LOADS

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ABSTRACT

Battery-pack thermal management must limit peak temperature, suppress cell-to-cell gradients, and recover heat over repeated cycles. This paper presents an empirical secondary-data synthesis of published experimental and computational studies of phase-change-material (PCM) cooling combined with liquid cooling. No new cells were tested and no CFD runs were performed; reported values were extracted without pooling incompatible tests. Evidence includes triplicate 2C tests on three parallel 18650 cells at 20 °C, a validated channel-resolved model, a 96-cell 21700 pack simulated over three 2C-discharge/0.5C-charge cycles, and experiments on five-cell prismatic modules. In the matched test, maximum surface temperatures were 126.1 °C for natural convection, 73.6 °C for silicone oil, 59.4 °C for thermal adhesive, and 52.7 °C for PCM. PCM sustained the reported post-discharge 30–50 °C interval for 56 min, although uniformity depended on direction and melting progression. A numerical channel-D case reported 41.2 °C after 30 min and identified 0.108 L/min as an efficient flow, with smaller gains at higher rates. In the 96-cell model, cycle peaks rose from 46.22 to 49.93 °C; pack temperature was reported below 30 °C at cycle endpoints. Evidence supports a mechanism-level relationship: PCM buffers transient heat, while liquid circulation rejects heat and restores latent capacity. Cell formats, loads, and metrics differ, precluding a universal effect estimate. Source inconsistencies, unavailable raw records, and the distinction between PCM-model validation and

numerical hybrid-channel testing are documented. The synthesis identifies design implications and validation needs for future design.

Keywords: *Lithium-ion battery¹; Battery thermal management²; Phase change material³; Liquid cooling⁴; Hybrid cooling⁵; Thermal uniformity⁶; Secondary-data synthesis⁷.*

1. INTRODUCTION

1.1 Battery heat, gradients, and performance indicators

During charge and discharge, irreversible Joule and polarization heat combine with reversible entropic heat, so electrochemical state, current, and temperature interact rather than behave as fixed heat source. Energy-balance formulations and electrothermal models provide the basis for deriving heat generation and predicting cell response [1], [2]. Elevated temperature accelerates degradation and can trigger exothermic failure propagation; safety studies consequently emphasize hot spots and module gradients [3], [4]. Thermal-management methods are therefore assessed against several outcomes: peak cell temperature, cell-to-cell and within-cell temperature difference, thermal buffering, and energy needed to circulate coolant. A low peak alone is insufficient if cold regions and hot spots diverge or the latent store cannot recover between cycles. This study uses those complementary indicators to organize literature.

1.2 Why couple PCM and liquid cooling?

Liquid cooling transfers heat rapidly and is controllable, but channels, pumps, seals, parasitic power, and coolant distribution add mass and complexity [5]–[7]. PCM adds passive thermal storage: latent heat absorbs a transient load near the melt interval and can reduce short-term temperature excursions [8], [9]. Yet low conductivity localizes melting; once latent capacity is saturated, peak temperature can rise. Composite PCM and fins or foam can improve conduction, though added mass, leakage risk, and manufacturing interfaces remain [10], [11]. Hybrid PCM–liquid concepts pair buffering near the cells with active heat rejection and latent-heat recovery. Reviews map a broad design space, but reveal inconsistent cell formats, rates, ambient conditions, and reporting conventions [12]–[16]. Thus, the core relationship tested here is not that hybrid cooling always wins, but that its advantage depends on thermal load, flow distribution, and the availability of regeneration during rest or charging.

1.3 Research questions and contribution

This paper addresses a practical evidence gap: numerical reports describe many channel and PCM variants, whereas experiments often test a specific cell geometry and a limited duty cycle. The analysis asks three linked questions. First, how do reported peak temperatures and thermal-buffer durations differ among air, silicone oil, thermal adhesive, and PCM under a matched 2C experiment? Second, do published hybrid systems preserve

uniformity and recover PCM capacity under repeated charge–discharge operation? Third, what do the available channel and flow data imply about diminishing returns? The contribution is a transparent, secondary-data reanalysis connecting those questions through five tables and five derived figures. Results are not represented as new experiments: measured and simulated evidence are labeled separately, missing raw data are acknowledged, and incompatible outcomes are not pooled into one effect estimate.

2. LITERATURE SURVEY

2.1 Experimental characterization

Experimental evidence spans modules and heaters. Kong et al. combined experiments with modeling and reported a modelled 41.1 °C peak and a 4 °C spread at 3C and 30 °C ambient; active cooling also recharged PCM during 0.5C charging [17]. Hekmat and Molaeimanesh compared seven cooling cases on five prismatic cells, finding that PCM-only limited maximum temperature to 32 °C and maximum cell spread to 1.2 °C, but passive cooldown to 30 °C was slower than hybrid arrangements [18]. Zhang et al. tested 106 18650 cells in an integrated PCM, heat-spreader, thermal-column, and mini-channel architecture; hybrid cooling lowered steady-state peak temperature and module nonuniformity relative to liquid-only cooling under cyclic operation [19]. Later cold-plate and composite-PCM studies support the importance of contact resistance and test-specific control [20], [21]. These experiments support physical credibility but differ in chemistry, shape, heat load, and temperature placement, limiting direct ranking across tested thermal conditions.

2.2 Computational characterization and repeated duty

Computational work adds spatial resolution and parametric coverage. An et al. modeled composite PCM with liquid cooling for a battery module [22], while Ping et al. explicitly considered non-uniform heat generation [23]. Zhang et al. simulated a 96-cell 21700, 6P16S pack over three discharge/charge cycles, reporting successive peaks of 46.22, 49.37, and 49.93 °C and recovery below 30 °C after each cycle [24]. Hyun et al. combined material-comparison experiments with CFD validation and a separate channel-design case: the validated PCM prediction was 50.6 °C versus 51.2 °C measured, while hybrid channel comparisons were numerical [25]. This distinction matters: calibration against a PCM discharge test does not independently validate every hybrid channel, pump load, or multi-cycle recovery scenario.

2.3 Design levers and evidence gap

Recent computational studies indicate that optimized geometry, not PCM presence alone, is decisive: wavy channels, fins, and channel arrangement influence peak temperature, temperature spread, pressure loss, and melt fraction [26]–[30]. Fins and conductive frameworks help distribute latent storage [27], [29], [30], whereas encapsulation shape and flow condition alter the passive/active balance [28]. Review studies agree that liquid

cooling can regenerate PCM and PCM can flatten transients, but also stress the absence of a uniform benchmark protocol [12], [13], [15], [16]. Prior work therefore supports mechanisms more strongly than a universal numerical effect size. The present synthesis treats cross-study temperature comparisons as contextual, not like-for-like, and gives greater weight to within-study contrasts with a shared cell format, ambient temperature, and a discharge-rate protocol.

3. METHODOLOGY

Targeted publisher-page searches through 8 October 2026 used “battery thermal management,” “PCM liquid cooling,” and “hybrid battery thermal management,” paired with “experimental” or “CFD.” No new experiments or simulations were run. We retained peer-reviewed articles with quantitative battery-temperature, uniformity, cycle, flow, or validation outcomes for PCM, liquid, or coupled cooling. Core records were Kong et al. [17], Hekmat and Molaeimanesh [18], Zhang et al. [19], Zhang et al.’s cycle model [24], and Hyun et al.’s experiment/CFD study [25]. Sources [20]–[23], [26]–[30] contextualized design; foundational studies [1], [2], [9] informed interpretation. Only traceable results were included.

For each record, we transcribed cell geometry and count, chemistry, C-rate, ambient temperature, evidence mode, cooling medium, duration, maximum temperature, directional temperature spread, buffering interval, liquid fraction, coolant rate, and cycle-end temperature. Values remain as published and are not pooled across cell types. Rounded narrative values are marked “≈” or described. Hyun et al.’s triplicate-average material test used three parallel 18650 cells; its channel comparison was numerical, not an experimental hybrid-pack test. Units were standardized to °C, minutes, and L/min when directly convertible; mass flow in kg/s was retained. Missing raw time series and replicate-level observations were logged.

We recalculated within-study temperature differences by subtraction; percentages were not recomputed when denominator definitions or source arithmetic were unclear. Raw replicates and comparable variance estimates were unavailable, so no standard errors, pooled effects, significance tests, or meta-regression were produced. Figures 2–5 replot published values or intervals; Figure 1 is an original mechanism schematic. Comparisons address direction and trade-offs, not cross-study rank. Rounded channel claims and inconsistent percentage reductions are disclosed. Findings generate design hypotheses and validation priorities, not universal performance guarantees or safety certification. This approach prioritizes source traceability and prevents mixing measured and simulated data as though equivalent.

4. DATA COLLECTION AND ANALYSIS

The analysis base is intentionally small and heterogeneous. Table 1 preserves the experimental/computational context instead of presenting the reports as interchangeable observations. This separation is central to interpreting the title’s “computational and experimental” characterization.

Table 1: Evidence provenance and comparability of the core studies

Study / evidence mode	Pack and operating condition	Reported outcome used here	Comparability caveat
Kong et al. [17] model + validation experiment	Hybrid PCM/liquid pack; 3C discharge, 30 °C ambient; 0.5C charge recovery	Modelled Tmax 41.1 °C; ΔT 4 °C at discharge end; PCM latent heat recovered during charge	Geometry and exact sample details differ from the focal 18650 tests
Hekmat and Molaeimanesh [18] experiment	Five high-capacity prismatic cells; seven active, passive, hybrid, and ventilation cases	PCM-only Tmax 32 °C and ΔT_{max} 1.2 °C; hybrid cases cooled to 30 °C faster	Different chemistry, scale, and test schedule; hybrid exact peak not in accessible summary
Zhang et al. [19] experiment	106 18650 test batteries; PCM, heat-spreading plate, thermal columns, bottom mini-channel plate	Hybrid lowered steady-state peak temperature and nonuniformity versus liquid-only; sustained cyclic control	Abstract does not provide matched numerical endpoints
Zhang et al. [24] CFD	96 × 21700, 6P16S; 2C discharge/0.5C charge; 20 °C; three cycles	Cycle Tmax: 46.22, 49.37, 49.93 °C; cycle-end pack temperature <30 °C	Numerical repeated-cycle result; not an independent experimental validation
Hyun et al. [25] experiment + CFD	Three 18650 cells in parallel; 2C; 20 °C; triplicate-average materials test	Measured media comparison plus numerical channel A–D study; PCM model Tmax 50.6 °C vs 51.2 °C measured	Channel-D hybrid result is numerical; material test is not a full vehicle pack

Table 1 shows a two-level evidence chain. Measurements characterize actual materials and modules, whereas several system-level cycle and channel advantages come from CFD. Hyun et al. [25] tested PCM, oil, adhesive, and air experimentally, but their liquid-channel geometry comparison was numerical; Zhang et al. [24] is an all-CFD cycle study. Kong [17] and Hekmat [18] provide direct physical hybrid evidence. Model agreement for PCM discharge does not independently validate pump demand, cold-plate pressure loss, multi-cycle phase recovery, or field durability. The following tables therefore identify evidence mode at each step.

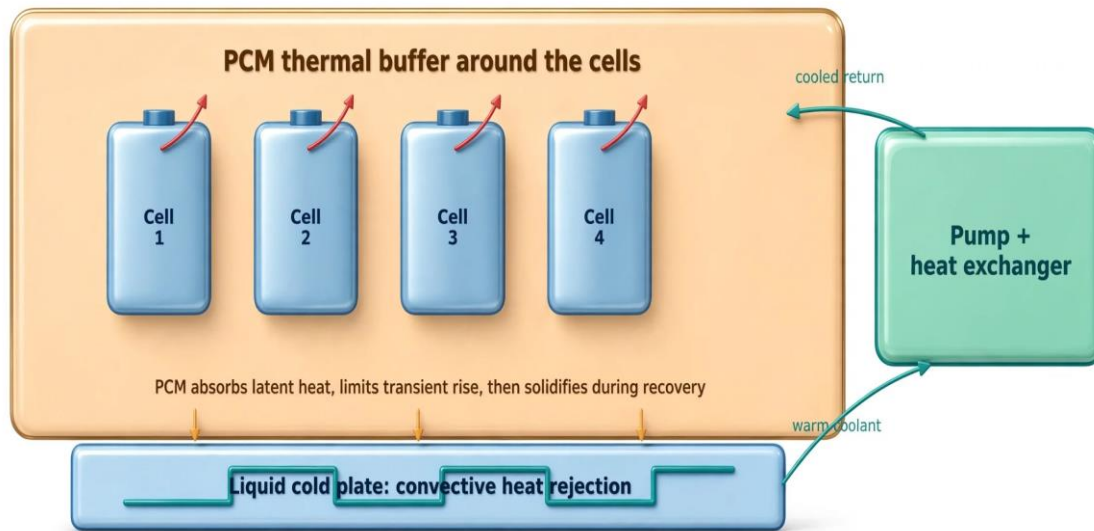


Figure 1: Conceptual heat-storage and heat-rejection pathway in a hybrid PCM–liquid BTMS (not to scale).

Figure 1 presents the governing heat path, not a tested geometry. Cells generate heat during discharge; surrounding PCM absorbs sensible and latent energy, moderating short transients and distributing heat among cells. A cold plate conducts heat from PCM, while circulating coolant transports it to a heat exchanger. During charging or rest, the active loop removes stored energy and re-solidifies PCM, restoring latent capacity for subsequent loads. The schematic summarizes mechanisms supported across the reviewed studies; it is not dimensioned and does not imply cited experiments used this exact arrangement or achieved identical performance. This is conceptual, not a tested prototype.

4.1 Within-study peak-temperature comparison

Table 2: Maximum surface temperature under the matched 2C material test [25]

Cooling medium	Maximum surface temperature (°C)	Absolute difference from air (°C)	Evidence note
Natural convection (air)	126.1	Reference	Experimental; 20 °C ambient
Silicone oil	73.6	–52.5	Experimental; same cell assembly and load
Thermal adhesive	59.4	–66.7	Experimental; same cell assembly and load
Paraffin PCM (≈40 °C melt point)	52.7	–73.4	Experimental; lowest reported peak

At the common 2C condition, PCM's 52.7 °C peak is 73.4 °C below the natural-convection endpoint; adhesive is 66.7 °C lower and oil 52.5 °C lower. These are absolute Celsius differences, not ratios. Hyun et al. report triplicate-average response, but replicate-level values and standard deviations are unavailable in the extracted record. A source arithmetic inconsistency remains: percentage-reduction statements do not match the listed maxima under direct Celsius arithmetic. Since temperature ratios depend on scale and the denominator definition is not stated, this synthesis avoids percentage claims. The peak ranking is clear within this test, but it does not imply the same ranking for uniformity, energy use, or full-pack durability.

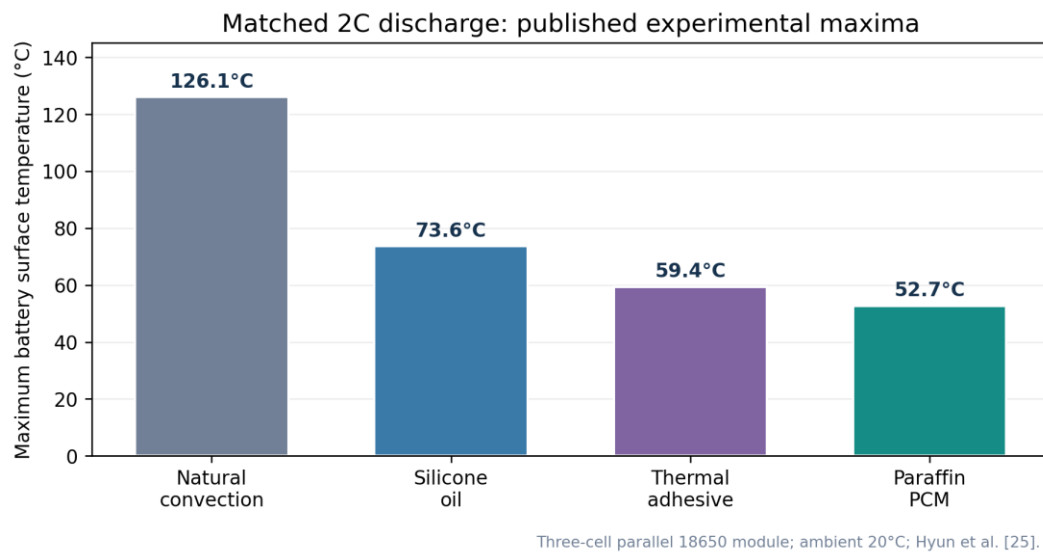


Figure 2: Published maximum surface temperatures for four cooling media during a matched 2C discharge [25].

Figure 2 replots four reported maximum surface temperatures from a matched 2C comparison experiment. The descending sequence is natural convection, silicone oil, thermal adhesive, and paraffin PCM, with PCM producing the lowest stated peak. Because cell assembly, ambient condition, and discharge rate were shared, this is the strongest within-study ranking in the synthesis. It is not a comparison of complete systems: the test used three parallel 18650 cells, and pump energy, pack-scale pressure loss, and long-term PCM regeneration were not measured. Values are endpoints; the source's percentage-reduction statements do not reconcile arithmetically with these maxima. This distinction limits engineering transfer.

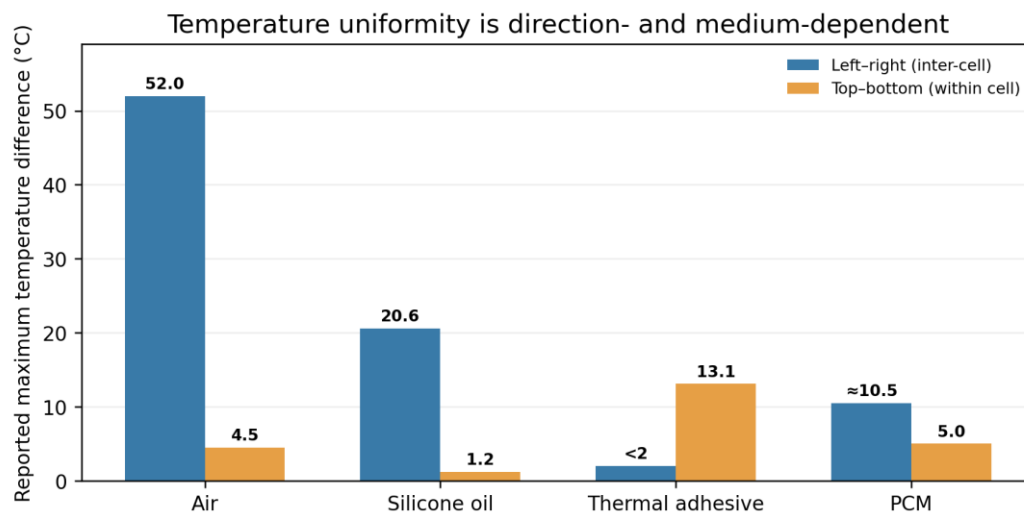
4.2 Temperature uniformity and post-discharge buffering

Table 3: Directional temperature differences and reported 30–50 °C maintenance time [25]

Cooling medium	Left–right inter-cell ΔT max (°C)	Top–bottom within-cell ΔT max (°C)	30–50 °C interval after discharge (min)
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Natural convection (air)	52.0 (at 30 min)	4.5	36
Silicone oil	20.6	1.2	43
Thermal adhesive	<2	13.1	49
PCM	≈10.5 late; <5 during first 20 min	5.0	56

PCM extends the reported 30–50 °C maintenance interval by 20 min relative to air; adhesive adds 13 min and silicone oil 7 min. The result is consistent with latent heat release during cooling, but buffering should not be confused with active heat rejection. Uniformity is anisotropic: adhesive suppresses lateral differences yet leaves a larger top–bottom gradient, while silicone oil performs best vertically. PCM starts relatively uniform and becomes less uniform as melting concentrates near hot cells. Because the source reports maxima from different parts of the discharge trace, Table 3 is used as a directional comparison, not a synchronized four-way snapshot.



Maxima reported over different intervals in the same study; PCM left-right ≈10.5°C late in discharge; adhesive value is an upper bound.

Figure 3: Reported maximum temperature spread by cooling medium and measurement direction [25].

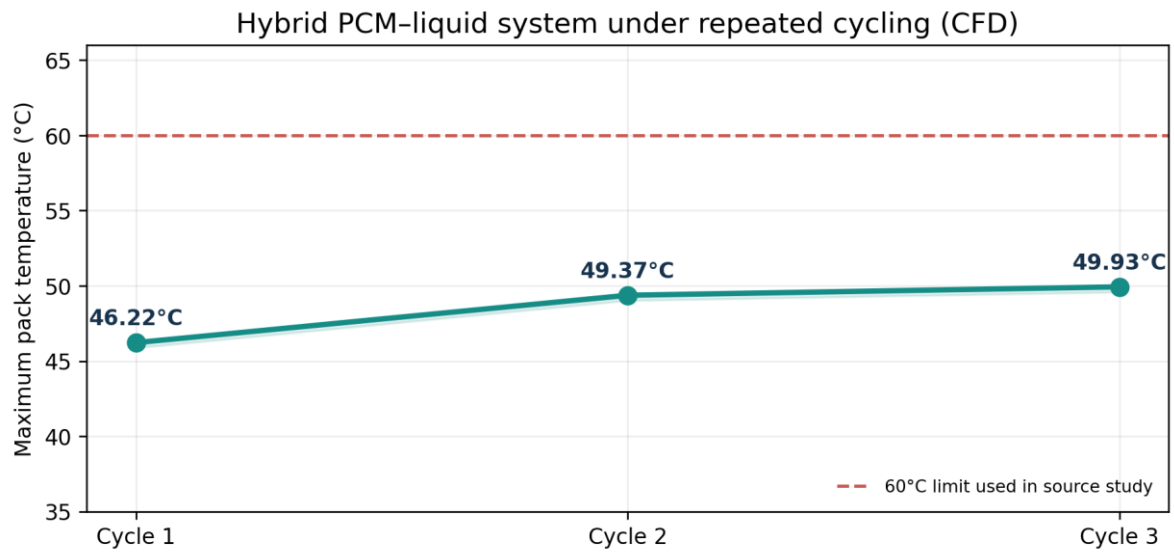
Figure 3 contrasts left–right inter-cell and top–bottom within-cell temperature differences reported for each medium. The results show why peak temperature and uniformity should not be collapsed into one score: adhesive limits lateral spread below 2 °C but reaches a 13.1 °C vertical difference, while silicone oil has the smallest vertical spread. PCM initially keeps lateral variation below 5 °C, then reaches approximately 10.5 °C as melting progresses. These maxima come from different intervals, so they are directional indicators, not simultaneous measurements. The chart highlights anisotropic heat-transfer paths and localized phase-change saturation. They remain separate design metrics.

4.3 Repeated-cycle evidence and cross-study comparison

Table 4: Repeated-duty and hybrid-system outcomes reported across studies

Study / mode	Duty / module context	Quantitative result	Interpretation
Kong et al. [17] model + validation experiment	3C discharge, 30 °C ambient; followed by 0.5C charge	Modelled 41.1 °C Tmax; 4 °C spread at discharge end	Hybrid model predicts peak control and PCM regeneration; distinct operating context
Hekmat and Molaeimanesh [18] experiment	Five prismatic cells; seven cooling cases	PCM-only: 32 °C Tmax, 1.2 °C Δ Tmax; hybrid returned to 30 °C faster	A measured hybrid cooldown advantage; source summary does not give hybrid peak
Zhang et al. [19] experiment	106 18650 test batteries; steady and cyclic tests	Hybrid lower Tmax and nonuniformity than liquid-only	Pack-scale physical support; numeric values not available in abstract
Zhang et al. [24] CFD	96-cell 21700 pack; three 2C/0.5C cycles	Tmax 46.22 → 49.37 → 49.93 °C; cycle-end <30 °C	Three-cycle simulation suggests recovery with modest peak drift
Hyun et al. [25] experiment + CFD	3P 18650; 2C; PCM validation and separate channel study	PCM model 50.6 °C vs 51.2 °C measured (0.6 °C gap); channel D = 41.2 °C at 30 min	Validation is for the PCM case; channel-D hybrid performance is numerical

The repeated-cycle model reaches its highest peak in cycle three, 3.71 °C above cycle one, even though the pack is reported to return below 30 °C at each cycle endpoint [24]. The output suggests that recharge-phase cooling can reset the latent store, but three modeled cycles cannot establish lifetime stability. Kong et al. provide an independent hybrid test/model comparison at a hotter ambient temperature and higher discharge rate [17]; Hekmat et al. offer measured prismatic evidence for faster cooldown [18]. Their results support the mechanism, not a pooled numerical effect, because module sizes and instrumentation differ [19], [20], [21].



2C discharge / 0.5C charge; ambient 20°C; Zhang et al. [24]. End-of-cycle pack temperature reported <30°C.

Figure 4: Maximum pack temperature across three repeated cycles in the 96-cell numerical study [24].

Figure 4 shows pack peak temperatures across three consecutive modeled cycles in Zhang et al. The increase from 46.22 °C to 49.93 °C indicates modest accumulation across repeated duty, while reported endpoint temperature falls below 30 °C after each charge/discharge sequence. All peaks remain below the 60 °C limit used in that paper, but the pattern does not establish indefinite steady operation: only three cycles were simulated, and first-to-third peak drift is visible. The figure links latent-heat recovery to cycling while retaining the distinction between a numerical scenario and long-duration experimental durability. Longer experiments are still necessary.

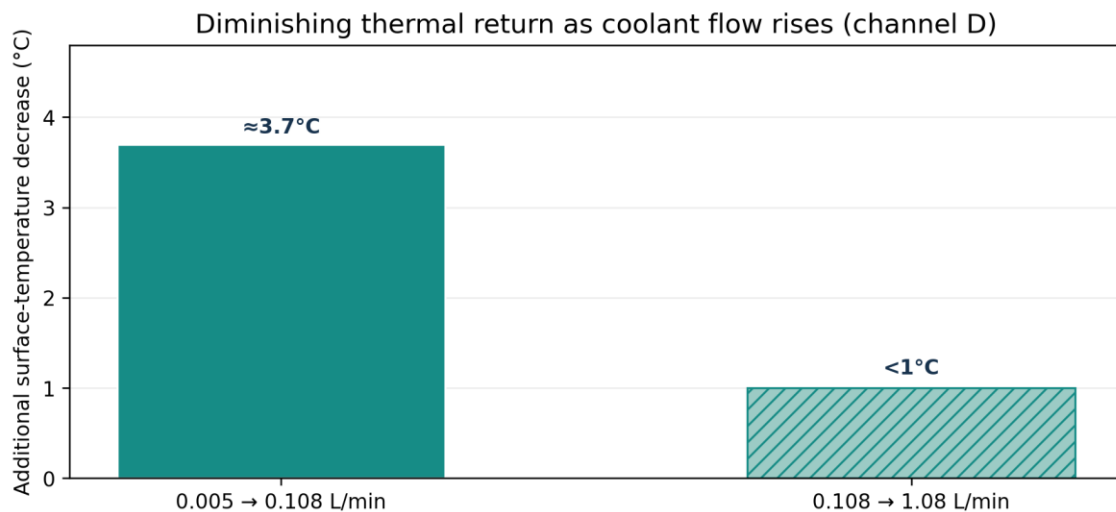
4.4 Channel geometry and coolant-flow trade-off

Table 5: Channel-design and flow-response evidence for the numerical channel-D case [25]

Design variable / condition	Published value	Observed thermal response	Data-analysis implication
Wetted area, channels A–D	A: 1560; B: 1509; C: 1719; D: 1698 mm ²	D was reported as most effective although C had the largest area	Area alone does not explain performance; routing and distribution matter
PCM-only vs channel D at 30 min	PCM-only ≈49 °C (text); D = 41.2 °C (table)	Source narrative reports up to ≈9 °C improvement	Rounded prose and tabulated point are not exactly reconcilable
Low-to-moderate flow increase	0.005 → 0.108 L/min	Surface temperature fell by ≈3.7 °C	Largest reported marginal benefit occurs before the knee
Higher flow increase	Above 0.108 L/min (tested up to 1.08 L/min)	Additional thermal decrease <1 °C; source identifies 0.108 L/min as efficient	Further flow may add pumping demand with little thermal return

Channel D transfer metrics at 30 min	$T = 41.2\text{ }^{\circ}\text{C}$; $Nu = 68$; $h = 209.2\text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	Highest cooling effectiveness among A–D in the reported comparison	Metrics characterize the modeled surface/flow case, not a measured pack-level COP
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The channel comparison shows that contact area is not a sufficient design proxy: configuration C had the largest wetted area, whereas D was reported to cool most effectively [25]. Text reports approximately $49\text{ }^{\circ}\text{C}$ for PCM-only and a D-channel surface temperature of $41.2\text{ }^{\circ}\text{C}$ in the table; the exact subtraction from the rounded PCM value is about $7.8\text{ }^{\circ}\text{C}$, while the paper’s narrative describes an improvement of up to $9\text{ }^{\circ}\text{C}$. This synthesis preserves both reports rather than manufacturing precision. Flow response is nonlinear: the initial increase to 0.108 L/min provides most of the observed reduction; higher flow adds less than $1\text{ }^{\circ}\text{C}$ of thermal improvement. Pump input and pressure loss must still be measured before calling this a system-level optimum.



Hyun et al. [25] report the first interval as a marked reduction and further gains below 1°C ; second bar is an upper bound.

Figure 5: Marginal temperature reduction with increased coolant flow in channel D [25].

Figure 5 plots reported channel-D cooling gains with rising flow. Increasing flow from 0.005 to 0.108 L/min lowers surface temperature by approximately $3.7\text{ }^{\circ}\text{C}$; increasing it further to 1.08 L/min yields less than $1\text{ }^{\circ}\text{C}$ additional reduction. The hatched second bar marks an upper bound, not an exact value. The response knee identifies 0.108 L/min as an efficient point for this geometry, not a universal optimum across packs, coolants, or pumps. The source provides no paired pump-power or pressure-loss curves, so this comparison shows diminishing thermal return, not a complete system-energy optimum.

5. DISCUSSION

5.1 Critical comparison with published work

Matched 2C material results rank peak temperatures: PCM (52.7 °C), adhesive (59.4 °C), silicone oil (73.6 °C), and natural convection (126.1 °C). This ranking does not extend to every objective. PCM retained the longest post-discharge 30–50 °C interval (56 min), consistent with latent-heat buffering described in PCM studies and reviews [9]–[13]. Directional data show adhesive produced the smallest lateral spread (<2 °C), while silicone oil gave the smallest top–bottom spread (1.2 °C); PCM’s late-discharge lateral and vertical spreads rose to about 10.5 and 5 °C as melting localized [25]. Thus, low peak temperature is not synonymous with uniformly low gradients. The channel-D numerical case lowered the 30-min surface temperature to 41.2 °C and showed a pronounced flow-rate knee near 0.108 L/min [25]. This is consistent with Kong et al.’s flow-controlled hybrid strategy, which modelled 41.1 °C and 4 °C spread at 3C and 30 °C ambient [17], and with studies finding channel topology and non-uniform heat generation important [22], [23], [26], [30]. It is not a direct replicate: cell architecture, load, and measurement definition differ. The cyclic 96-cell model provides a separate system-level signal: peaks rose 3.71 °C from cycle one to three but ended below 30 °C after each simulated cycle [24]. Hekmat’s experiment shows why absolute values need context: its PCM-only five-cell prismatic case was 32 °C with 1.2 °C spread, and hybrid arrangements cooled back to 30 °C faster under a different protocol [18]. Earlier 106-cell experiments and embedded-PCM cold plates support active/passive complementarity [19]–[21]. Across studies, hybridization couples a transient buffer to a controllable heat sink; it does not guarantee a percentage improvement. Prior studies report diminishing flow returns when coolant resistance is no longer dominant [15], [26].

5.2 Limits, interpretation, and design implications

Interpretation is limited by source quality and transferability. The 2025 study’s stated percentage reductions cannot be reproduced from its listed Celsius maxima; we retain absolute temperatures and avoid unsupported percentages. Its 0.6 °C model–measurement gap validates the PCM discharge case, not channel D, which remains numerical. Across papers, maxima, directional gradients, and “isothermal maintenance” use different definitions; raw time-aligned series and replicate variance are unavailable. The 96-cell simulation, five-cell prismatic test, and three-cell cylindrical test cannot be pooled. Pump power, channel pressure loss, PCM mass, aging, leakage, and abuse response were not jointly measured. Other high-rate results indicate cooling may still exceed recommended temperatures at $\geq 4C$ [25]. Design guidance is conditional: choose the melting range for the duty cycle, distribute conductive paths to limit isolated melt pockets, and provide enough flow to regenerate latent capacity; optimize flow only with pump energy and pressure loss included. Future pack tests should compare PCM-only, liquid-only, and hybrid modes at matched current, ambient, and geometry over repeated cycles, publishing synchronized raw temperatures, uncertainty, coolant calorimetry, and pump power. CFD should then be validated against passive

and active hybrid measurements. This would replace a mechanism-level synthesis with comparable system-level evidence during actual service.

6. CONCLUSION

This secondary-data synthesis finds that hybrid PCM–liquid cooling is supported by a coherent thermal mechanism, but not one transferable performance number. In the matched 2C experiment, PCM produced the lowest reported peak (52.7 °C) and longest post-discharge 30–50 °C buffering interval (56 min). However, temperature uniformity varied by direction: adhesive performed best laterally and silicone oil vertically, while PCM gradients increased as melting localized. Hybrid studies indicate the complementary role of liquid flow. A channel-D CFD case reported 41.2 °C after 30 min and diminishing gains beyond about 0.108 L/min; repeated-cycle modeling kept cycle-end temperatures below 30 °C as peaks rose modestly over three cycles. Experiments on prismatic and large cylindrical modules also report improved heat removal or faster recovery, but operating conditions differ. The central relationship is conditional: PCM absorbs transient heat and moderates temperature rise; liquid cooling rejects heat and restores latent capacity. Broader claims are limited because the channel-D result is numerical, reported percentage reductions are arithmetically ambiguous, replicate variance is unavailable, and pump energy, aging, leakage, and abuse response are incomplete. Designers should co-optimize PCM melting range, conductive pathways, channel distribution, and flow for a defined duty cycle rather than maximize flow or PCM mass. Next, pack-scale experiments should compare PCM-only, liquid-only, and hybrid modes at matched current, ambient temperature, and geometry over repeated cycles, publishing synchronized raw measurements and uncertainty. The present synthesis guides validation; it does not constitute new experimental work or safety certification for any deployed pack.

7. REFERENCES

- [1] D. Bernardi, E. Pawlikowski, and J. Newman, “A general energy balance for battery systems,” *J. Electrochem. Soc.*, vol. 132, no. 1, pp. 5–12, 1985, doi: 10.1149/1.2113792.
- [2] C. R. Pals and J. Newman, “Thermal modeling of the lithium/polymer battery: I. Discharge behavior of a single cell,” *J. Electrochem. Soc.*, vol. 142, no. 10, pp. 3274–3281, 1995, doi: 10.1149/1.2049974.
- [3] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, and C. Chen, “Thermal runaway caused fire and explosion of lithium ion battery,” *J. Power Sources*, vol. 208, pp. 210–224, 2012, doi: 10.1016/j.jpowsour.2012.02.038.
- [4] X. Feng et al., “Investigating the thermal runaway mechanisms of lithium-ion batteries based on thermal analysis database,” *Appl. Energy*, vol. 246, pp. 53–64, 2019, doi: 10.1016/j.apenergy.2019.04.009.
- [5] G. Xia, L. Cao, and G. Bi, “A review on battery thermal management in electric vehicle application,” *J. Power Sources*, vol. 367, pp. 90–105, 2017, doi: 10.1016/j.jpowsour.2017.09.046.

- [6] Z. Wang and C. Du, “A comprehensive review on thermal management systems for power lithium-ion batteries,” *Renew. Sustain. Energy Rev.*, vol. 139, Art. no. 110685, 2021, doi: 10.1016/j.rser.2020.110685.
- [7] M. Shahjalal, T. Shams, M. E. Islam, W. Alam, M. Modak, S. B. Hossain, V. Ramadesigan, M. R. Ahmed, H. Ahmed, and A. Iqbal, “A review of thermal management for Li-ion batteries: Prospects, challenges, and issues,” *J. Energy Storage*, vol. 39, Art. no. 102518, 2021, doi: 10.1016/j.est.2021.102518.
- [8] J. Chen et al., “Effects of different phase change material thermal management strategies on the cooling performance of the power lithium-ion batteries: A review,” *J. Power Sources*, vol. 442, Art. no. 227228, 2019, doi: 10.1016/j.jpowsour.2019.227228.
- [9] S. Al Hallaj and J. R. Selman, “A novel thermal management system for electric vehicle batteries using phase-change material,” *J. Electrochem. Soc.*, vol. 147, no. 9, pp. 3231–3236, 2000, doi: 10.1149/1.1393888.
- [10] J. Luo, D. Zou, Y. Wang, S. Wang, and L. Huang, “Battery thermal management systems (BTMs) based on phase change material (PCM): A comprehensive review,” *Chem. Eng. J.*, vol. 430, Art. no. 132741, 2022, doi: 10.1016/j.cej.2021.132741.
- [11] G. Murali, G. S. N. Sravya, J. Jaya, and V. Naga Vamsi, “A review on hybrid thermal management of battery packs and its cooling performance by enhanced PCM,” *Renew. Sustain. Energy Rev.*, vol. 150, Art. no. 111513, 2021, doi: 10.1016/j.rser.2021.111513.
- [12] C. Zhao, B. Zhang, Y. Zheng, S. Huang, T. Yan, and X. Liu, “Hybrid battery thermal management system in electric vehicles: A review,” *Energies*, vol. 13, no. 23, Art. no. 6257, 2020, doi: 10.3390/en13236257.
- [13] Y. Zhao, X. Zhang, B. Yang, and S. Cai, “A review of battery thermal management systems using liquid cooling and PCM,” *J. Energy Storage*, vol. 76, Art. no. 109836, 2024, doi: 10.1016/j.est.2023.109836.
- [14] L. He, H. Jing, Y. Zhang, P. Li, and Z. Gu, “Review of thermal management system for battery electric vehicle,” *J. Energy Storage*, vol. 59, Art. no. 106443, 2023, doi: 10.1016/j.est.2022.106443.
- [15] J. R. Patel and M. K. Rathod, “Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries,” *J. Power Sources*, vol. 480, Art. no. 228820, 2020, doi: 10.1016/j.jpowsour.2020.228820.
- [16] J. Y. Lin, X. H. Liu, S. Li, C. Zhang, and S. C. Yang, “A review on recent progress, challenges and perspective of battery thermal management system,” *Int. J. Heat Mass Transf.*, vol. 167, Art. no. 120834, 2021, doi: 10.1016/j.ijheatmasstransfer.2020.120834.

- [17] D. Kong, R. Peng, P. Ping, J. Du, G. Chen, and J. X. Wen, “A novel battery thermal management system coupling with PCM and optimized controllable liquid cooling for different ambient temperatures,” *Energy Convers. Manage.*, vol. 204, Art. no. 112280, 2020, doi: 10.1016/j.enconman.2019.112280.
- [18] S. Hekmat and G. R. Molaeimanesh, “Hybrid thermal management of a Li-ion battery module with phase change material and cooling water pipes: An experimental investigation,” *Appl. Therm. Eng.*, vol. 166, Art. no. 114759, 2020, doi: 10.1016/j.applthermaleng.2019.114759.
- [19] H. Zhang, X. Wu, Q. Wu, and S. Xu, “Experimental investigation of thermal performance of large-sized battery module using hybrid PCM and bottom liquid cooling configuration,” *Appl. Therm. Eng.*, vol. 159, Art. no. 113968, 2019, doi: 10.1016/j.applthermaleng.2019.113968.
- [20] M. Akbarzadeh, T. Kalogiannis, L. Jin, D. Karimi, J. Van Mierlo, and M. Berecibar, “Experimental and numerical thermal analysis of a lithium-ion battery module based on a novel liquid cooling plate embedded with phase change material,” *J. Energy Storage*, vol. 50, Art. no. 104673, 2022, doi: 10.1016/j.est.2022.104673.
- [21] Z. Liu, J. Huang, M. Cao, G. Jiang, Q. Yan, and J. Hu, “Experimental study on the thermal management of batteries based on the coupling of composite phase change materials and liquid cooling,” *Appl. Therm. Eng.*, vol. 185, Art. no. 116415, 2021, doi: 10.1016/j.applthermaleng.2020.116415.
- [22] Z. An, X. Chen, L. Zhao, and Z. Gao, “Numerical investigation on integrated thermal management for a lithium-ion battery module with a composite phase change material and liquid cooling,” *Appl. Therm. Eng.*, vol. 163, Art. no. 114345, 2019, doi: 10.1016/j.applthermaleng.2019.114345.
- [23] P. Ping, Y. Zhang, D. Kong, and J. Du, “Investigation on battery thermal management system combining phase change material and liquid cooling considering non-uniform heat generation of battery,” *J. Energy Storage*, vol. 36, Art. no. 102448, 2021, doi: 10.1016/j.est.2021.102448.
- [24] Y. Zhang, Q. Fu, Y. Liu, B. Lai, Z. Ke, and W. Wu, “Investigations of lithium-ion battery thermal management system with hybrid PCM/liquid cooling plate,” *Processes*, vol. 11, no. 1, Art. no. 57, 2023, doi: 10.3390/pr11010057.
- [25] S. W. Hyun, J. H. Kim, and D. H. Shin, “Hybrid PCM–liquid cooling system with optimized channel design for enhanced thermal management of lithium-ion batteries,” *Energies*, vol. 18, no. 18, Art. no. 4996, 2025, doi: 10.3390/en18184996.
- [26] Y. Wang, Y. Wang, T. He, and N. Mao, “A numerical study on a hybrid battery thermal management system based on PCM and wavy microchannel liquid cooling,” *Renew. Energy*, vol. 235, Art. no. 121273, 2024, doi: 10.1016/j.renene.2024.121273.

- [27] P. Ping, R. Peng, D. Kong, G. Chen, and J. Wen, “Investigation on thermal management performance of PCM-fin structure for Li-ion battery module in high-temperature environment,” *Energy Convers. Manage.*, vol. 176, pp. 131–146, 2018, doi: 10.1016/j.enconman.2018.09.025.
- [28] M. Safdari, R. Ahmadi, and S. Sadeghzadeh, “Numerical investigation on PCM encapsulation shape used in the passive-active battery thermal management,” *Energy*, vol. 193, Art. no. 116840, 2020, doi: 10.1016/j.energy.2019.116840.
- [29] H. Liu, C. Jin, H. Li, and Y. Ji, “A numerical study of PCM battery thermal management performance enhancement with fin structures,” *Energy Rep.*, vol. 9, pp. 1793–1802, 2023, doi: 10.1016/j.egyr.2023.04.214.
- [30] H. Liu, S. Ahmad, Y. Shi, and J. Zhao, “A parametric study of a hybrid battery thermal management system that couples PCM/copper foam composite with helical liquid channel cooling,” *Energy*, vol. 231, Art. no. 120869, 2021, doi: 10.1016/j.energy.2021.120869.