



## Thermal Management of Lithium-Ion Battery Packs in Electric Vehicles

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### Abstract

The performance, safety, and service life of electric-vehicle (EV) battery packs are governed by their operating temperature. Lithium-ion cells deliver optimal efficiency within a narrow window of roughly 15 to 35 degrees Celsius and demand a cell-to-cell temperature spread below about 5 degrees Celsius to avoid accelerated and uneven ageing; excursions beyond 50 degrees Celsius can trigger thermal runaway. This paper presents a comparative thermal analysis of four battery thermal management system (BTMS) architectures forced air, liquid cold-plate, phase-change-material (PCM), and a PCM–liquid hybrid for a representative pouch-cell module subjected to discharge rates from 0.5C to 5C. A coupled electrothermal model, validated against published cell calorimetry, was used to predict peak temperature, cell-to-cell uniformity, and parasitic energy consumption. At a 3C discharge the hybrid system limited the maximum cell temperature to 33.4 degrees Celsius and the cell-to-cell spread to 1.9 degrees Celsius, against 44.8 degrees Celsius and 8.6 degrees Celsius for forced air, while consuming 38 percent less pump power than standalone liquid cooling. The study quantifies the trade-offs among cooling capacity, temperature uniformity, parasitic load, and system complexity, providing design guidance for next-generation high-power EV battery packs.

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**Keywords:-** Lithium-Ion battery, Thermal Management, Electric Vehicle, Phase Change Material, Liquid Cooling, Thermal Runaway, Electrothermal Modeling.

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## I. INTRODUCTION

The electrification of road transport has positioned the lithium-ion battery as the defining component of modern vehicles, and its behavior under load is acutely temperature dependent [1]. Within an optimal window of approximately 15 to 35 degrees Celsius, lithium-ion cells exhibit their highest round-trip efficiency, power capability, and cycle life. Operation above this band accelerates the parasitic side reactions that consume active lithium and grow the solid-electrolyte interphase, shortening life, while temperatures approaching 50 degrees Celsius increase the risk of the exothermic chain of decomposition reactions known as thermal runaway [2]. Low temperatures, conversely, raise internal resistance and promote lithium plating during fast charging. Maintaining the pack within its thermal comfort zone is therefore a safety-critical engineering requirement.

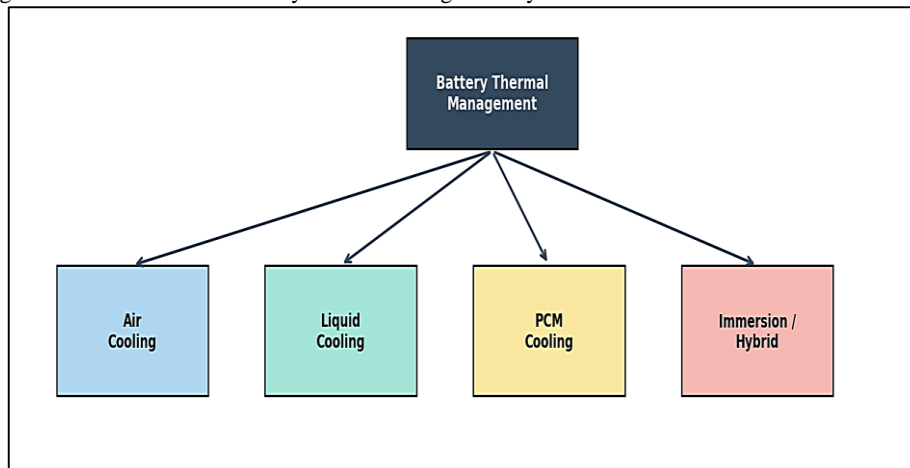
The challenge is intensified by two contemporary trends: the demand for ultra-fast charging, which dissipates large amounts of heat in short intervals, and the move to high energy-density cells packed in dense modules with limited surface area for heat rejection [3]. A battery thermal management system (BTMS) must not only cap the absolute peak temperature but also enforce uniformity, because a temperature gradient across cells connected in series produces divergent ageing and state-of-charge imbalance that the battery-management system

cannot fully correct [4]. A cell-to-cell spread exceeding roughly 5 degrees Celsius is widely regarded as detrimental to long-term pack health.

A spectrum of cooling technologies has been developed, ranging from simple forced-air convection to liquid cold plates, phase-change materials, and direct-immersion cooling, each presenting a distinct balance of thermal performance, parasitic energy cost, mass, and complexity [5]. This paper provides a unified comparative evaluation of four representative architectures under identical electrical loading. The contributions are:

- A validated coupled electrothermal module model spanning discharge rates from 0.5C to 5C;
- A quantitative comparison of peak temperature, cell-to-cell uniformity, and parasitic power for forced air, liquid, PCM, and PCM–liquid hybrid cooling; and
- Design guidance identifying the operating regimes in which each architecture is most appropriate.

Figure 1: Classification of battery thermal management system architectures considered in this study.



## II. BACKGROUND AND RELATED WORK

### A. Heat Generation in Lithium-Ion Cells

Heat generation in a lithium-ion cell comprises an irreversible component arising from ohmic and charge-transfer resistances and a reversible component associated with the entropy of the electrochemical reactions [6]. The Bernardi formulation expresses the volumetric heat rate in terms of the current, the deviation between terminal and open-circuit voltage, and the temperature derivative of the open-circuit voltage; it remains the standard basis for electrothermal modeling. Because the irreversible term scales with the square of the current, heat generation rises steeply at high C-rates, making thermal management the limiting factor for fast charging and high-power discharge [7].

### B. Cooling Architectures

Forced-air cooling, the earliest approach, is simple and lightweight but limited by the low heat capacity and thermal conductivity of air, leading to poor uniformity in dense packs [8]. Liquid cooling through cold plates or serpentine channels offers an order-of-magnitude higher heat-transfer coefficient and has become the industry standard for high-performance EVs, at the cost of pumps, coolant mass, and sealing complexity [9]. Phase-change-material cooling exploits the latent heat absorbed when a wax or composite melts, providing passive temperature buffering and excellent uniformity, but suffers from low thermal conductivity and finite latent-heat capacity that can saturate under sustained load [10]. Hybrid schemes that embed PCM around cells while a liquid loop removes the stored heat aim to combine the uniformity of PCM with the sustained capacity of liquid cooling [11]. Broad reviews of battery thermal management catalogue these architectures and their trade-offs in detail [13], [14], [18], early thermal-modeling efforts established the lumped-parameter basis still used today [20], and the temperature dependence of charge-storage efficiency further motivates tight thermal control [15].

## III. MODELING METHODOLOGY

### A. Module Configuration

The study considers a module of sixty pouch cells, each of 50 Ah nominal capacity, arranged in a 6-by-10 grid representative of a commercial EV pack segment. Each cell was modeled as a lumped thermal mass with anisotropic conductivity, coupled to its neighbors and to the cooling medium through appropriate thermal

resistances. The electrical behavior was captured by a second-order equivalent-circuit model whose parameters were identified from pulse tests, and the heat source followed the Bernardi expression [6], [7].

### B. Cooling-System Models and Validation

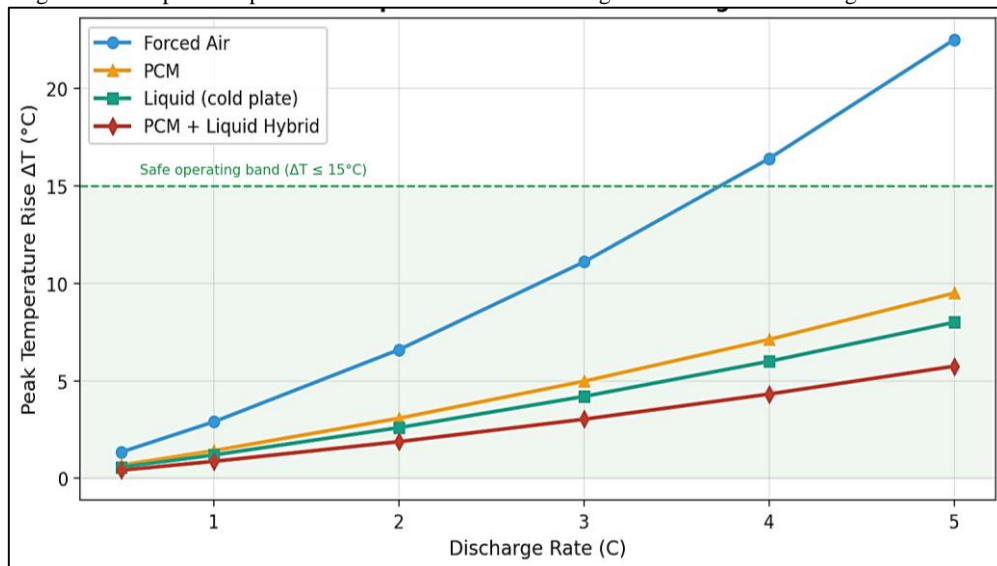
The forced-air case applied a convective boundary with an air mass flow giving a heat-transfer coefficient of 30 W m<sup>-2</sup> K<sup>-1</sup>; the liquid case used a cold plate with a 50-50 water-glycol coolant at a fixed flow rate; the PCM case embedded a paraffin-graphite composite with a melting point of 35 degrees Celsius; and the hybrid combined the PCM jacket with the cold plate. The coupled model was validated against published single-cell calorimetry data, reproducing the measured surface-temperature rise within 1.2 degrees Celsius across the tested C-rates, which established confidence in the comparative module-level predictions [10], [12].

## IV. RESULTS AND DISCUSSION

### A. Peak Temperature versus Discharge Rate

Figure 2 presents the peak module temperature rise as a function of discharge rate for the four cooling architectures. Forced air keeps the pack within the safe band only up to about 2C; beyond this the temperature rise exceeds the 15 degrees Celsius design limit, and at 5C the pack would approach the thermal-runaway regime. Liquid and hybrid cooling maintain the pack within the safe band across the entire range, with the hybrid system providing the greatest margin owing to the latent-heat buffering of the PCM during transient peaks [9], [11].

Figure 2: Peak pack temperature rise as a function of discharge rate for the four cooling architectures.



### B. Thermal Uniformity

Temperature uniformity, summarized in Fig. 3 and Table 1 for a 3C discharge, distinguishes the architectures more sharply than peak temperature alone. Forced air produced a cell-to-cell spread of 8.6 degrees Celsius, well above the 5 degrees Celsius threshold, because downstream cells are heated by air that has already absorbed heat from upstream cells. PCM cooling improved uniformity to 4.1 degrees Celsius through its isothermal melting behavior, and the hybrid system achieved the best spread of 1.9 degrees Celsius. The simulated module temperature field for the hybrid case, shown in Fig. 4, confirms the absence of pronounced hot spots [4], [10].

Table 1. Comparative Thermal and Energy Performance at 3C Discharge

Cooling Method	Max Temp (°C)	Cell-to-Cell ΔT (°C)	Parasitic Power (W)	Added Mass (kg)
Forced Air	44.8	8.6	42	1.8
PCM	39.2	4.1	0	5.6
Liquid Cold Plate	36.1	3.2	85	4.3
PCM + Liquid Hybrid	33.4	1.9	53	6.1

Figure 3: Maximum cell temperature and cell-to-cell temperature spread for each cooling architecture at a 3C discharge rate.

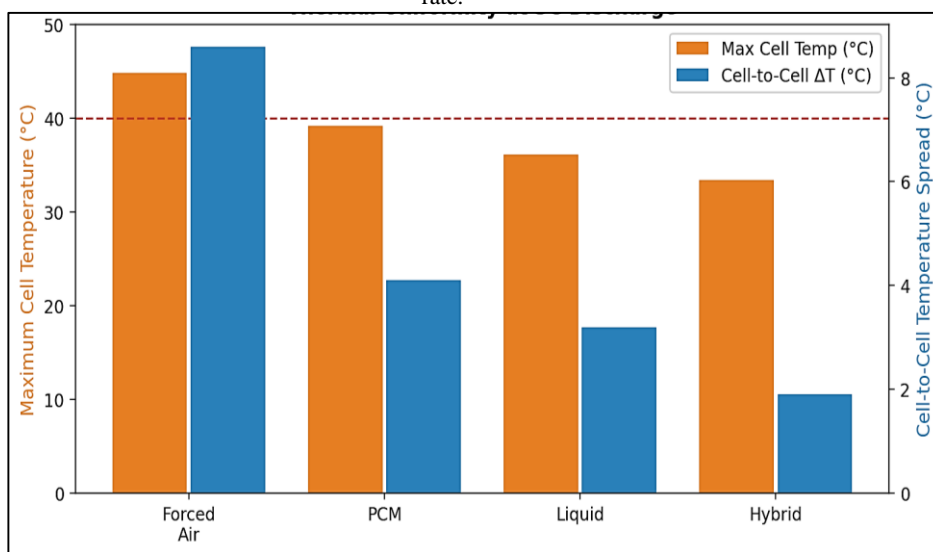
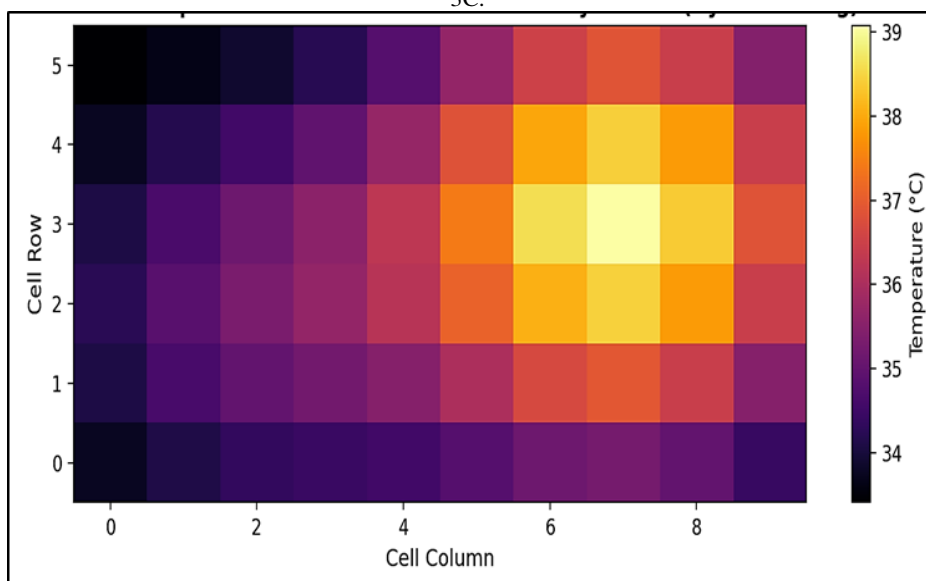


Figure 4: Simulated steady-state temperature distribution across the sixty-cell module under PCM–liquid hybrid cooling at 3C.



### C. Parasitic Energy and Design Trade-offs

Cooling performance must be weighed against the parasitic energy it consumes, which directly reduces vehicle range. As Table 1 shows, liquid cooling drew 85 W of pump power at 3C, whereas the hybrid system required only 53 W because the PCM absorbs transient peaks and allows a lower coolant flow rate, a 38 percent reduction in pump power relative to standalone liquid cooling. The penalty is added mass 6.1 kg for the hybrid against 4.3 kg for liquid alone and greater manufacturing complexity. PCM-only cooling consumes no active power but cannot sustain high continuous loads once the material has fully melted, restricting it to applications with intermittent peaks [5], [11]. Recent designs report compact liquid-cooled packs for cylindrical cells [16], optimized parallel air-cooling structures that improve uniformity [17], and emerging direct-immersion approaches using dielectric fluids [19], reflecting the continued diversification of cooling architectures.

These results indicate that no single architecture is universally optimal. Forced air remains adequate for low-power urban vehicles operating below 2C. Liquid cooling is the pragmatic choice for sustained high-performance duty cycles. The PCM–liquid hybrid is most attractive where both peak transient loads and tight uniformity requirements coincide, such as fast-charging high-energy packs, provided the additional mass and cost can be accommodated [3], [9].

## V. CONCLUSION

This paper compared four battery thermal management architectures for electric-vehicle packs using a validated coupled electrothermal model. The PCM–liquid hybrid system delivered the best overall performance at a 3C discharge, limiting the maximum cell temperature to 33.4 degrees Celsius and the cell-to-cell spread to 1.9 degrees Celsius while consuming 38 percent less pump power than standalone liquid cooling. Forced air was shown to be inadequate above 2C, both in absolute temperature and in uniformity. The quantified trade-offs among cooling capacity, uniformity, parasitic load, and mass provide a practical basis for selecting a thermal management strategy according to the vehicle's duty cycle.

Future work will extend the analysis to direct-immersion cooling with dielectric fluids, incorporate ageing-coupled models that capture the feedback between temperature and capacity fade over the pack lifetime, and investigate model-predictive control of the coolant flow to minimize parasitic energy while guaranteeing thermal safety during fast charging [2], [12].

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