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A Review of Battery Cooling Systems for Electric Vehicles

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Abstract
Battery thermal management is no longer a secondary subsystem in electric vehicles; it directly affects charging capability, usable energy, ageing, safety, and auxiliary energy consumption. This focused review compares the principal cooling approaches used for lithium-ion battery packs, including air cooling, indirect and direct liquid cooling, refrigerant cooling, phase-change materials, heat pipes, thermoelectric devices, and hybrid architectures. The literature is interpreted through a common set of engineering metrics: maximum cell temperature, temperature non-uniformity, hydraulic or auxiliary-energy penalty, packaging burden, controllability, safety, and manufacturability. Air cooling remains attractive where heat load and packaging complexity are modest, whereas liquid cold plates provide the most mature route for high-power automotive packs. Refrigerant and immersion concepts shorten the thermal path but raise sealing, dielectric, and control requirements. Passive devices such as phase-change materials and heat pipes can buffer transient peaks, yet they require a reliable heat-rejection or regeneration path for repeated duty. Recent work has increasingly shifted from single-parameter geometric studies toward multi-objective thermal-hydraulic optimization and surrogate-assisted design. The review therefore argues that future battery cooling should be assessed as a vehicle-level co-design problem rather than by peak temperature alone. Designs that retain thermal uniformity across fast charging, high ambient temperature, repeated drive cycles, and realistic pump or compressor limits are more relevant than isolated optimum points.

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1. Introduction

Lithium-ion batteries offer the energy and power density required by modern electric vehicles, but their electrochemical response is strongly temperature dependent. Excessive temperature accelerates side reactions and ageing, while large cell-to-cell temperature differences promote non-uniform current distribution and uneven degradation. A battery thermal management system (BTMS) must therefore do more than prevent overheating: it must limit the maximum temperature, maintain spatial uniformity, respond to transient load, and do so without imposing excessive mass or auxiliary energy. An early overview by Han *et al.* [1] grouped practical EV cooling into air, liquid, direct refrigerant, phase-change-material, thermoelectric, heat-pipe, and hybrid approaches. Broader reviews subsequently showed that the preferred architecture depends on heat load, ambient condition, battery format, charging rate, and vehicle-level integration [2–4].

The recent literature has also changed in emphasis. Rather than asking only which cooling medium gives the lowest temperature, current studies increasingly evaluate the thermal path, coolant distribution, energy penalty, packaging, and controllability of the complete subsystem. Akkuş and Işık [5] compared the principal BTMS families and stressed the need to match cooling intensity to the cell and operating condition. At vehicle level, Esen and Shabaneh [6] further highlighted the coupling of battery cooling with heat pumps, cabin thermal demand, cold-climate operation, and control strategy. These observations motivate a revie organized around engineering function rather than around isolated hardware concepts.

Despite this progress, the literature remains divided between broad technology reviews and method-specific design studies. Table 1 positions the present review against these main literature strands and makes explicit the gap addressed here.

Table 1: Literature positioning, unresolved gaps, and contribution of the present review.

Literature focus	Representative refs.	Established contribution	Remaining gap / role in this review
Broad BTMS reviews	[1-6]	Classify major active, passive, and hybrid cooling routes and summarize system-level trends.	Useful technology coverage, but engineering selection metrics and design-optimization evidence are not always connected in one comparison.
Air-cooling studies	[7, [8]	Clarify flow-distribution limits, cycle-life effects, and the operating envelope of air-based cooling.	Limited basis for comparing air cooling with higher-capacity liquid, refrigerant, and passive/hybrid routes.
Liquid-cooling reviews	[12, 13]	Develop detailed understanding of cold plates, channels, coolant paths, and structural optimization.	Strong within liquid BTMS, but less emphasis on cross-technology selection and integration with passive or hybrid concepts.
Heat-pipe / hybrid literature	[15, 17, 18, 21]	Demonstrates low-resistance heat transport and transient thermal buffering in passive or coupled architectures.	Recovery, auxiliary-energy demand, manufacturability, and repeated-duty performance are not consistently compared with active cooling.
Present review	[1-30]	Compares air, indirect/direct liquid, refrigerant, heat-pipe, thermoelectric, PCM, and hybrid approaches together with recent optimization evidence.	Uses a common engineering basis: Tmax, ΔTmax, pressure drop / auxiliary energy, mass and volume, safety, manufacturability, validation, and vehicle-level integration.

Accordingly, this paper provides a focused review of battery cooling systems for electric vehicles using 30 representative publications. The discussion compares active and passive cooling routes, identifies the design variables that control thermal and hydraulic performance, and examines the transition from component-level cooling toward hybrid and optimization-based solutions. Particular attention is given to metrics that can be compared across methods: maximum battery temperature, temperature difference, pressure drop or auxiliary power, mass and volume, safety, manufacturability, and the ability to recover after repeated thermal loads

2. Review Scope and Evaluation Framework

The comparison is based on engineering performance rather than a single thermal ranking. Maximum cell temperature (Tmax) is used as the primary safety and ageing indicator, whereas the maximum temperature spread (ΔTmax) reflects thermal uniformity. For forced-flow systems, pressure drop and pumping power are relevant because additional coolant velocity is not free. Refrigerant systems require compressor work and stable two-phase control. Passive devices must be judged by thermal-storage capacity, recovery time, and the ability to reject stored heat before the next high-load event. Packaging mass, volume, sealing, electrical isolation, serviceability, and manufacturability are treated as selection constraints rather than afterthoughts.

The literature set intentionally emphasizes studies published from 2020 onward together with recent contributions that directly address EV battery cooling. This is a focused critical review, not a bibliometric or systematic meta-analysis. Numerical results are therefore interpreted within their original boundary conditions; values obtained under different cell formats, C-rates, inlet temperatures, or coolant flow rates are not pooled as if they were directly equivalent.

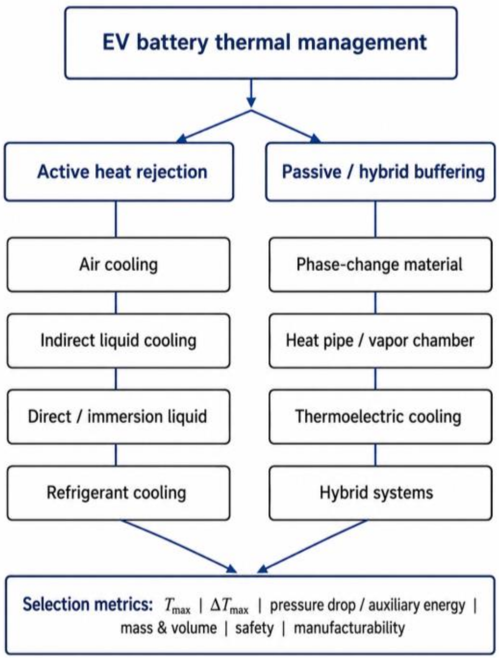

Fig 1: Functional classification of EV battery cooling approaches and the common engineering metrics used for technology selection.

Table 2: Engineering comparison of principal EV battery cooling approaches.

Method	Heat-removal mechanism	Main advantage	Main limitation
Air	Forced or natural convection	Low cost, simple, leak-free	Low heat capacity; flow maldistribution
Indirect liquid	Cold plate or jacket conduction + convection	High cooling capacity and mature control	Pressure drop, pump energy, sealing
Direct / immersion	Coolant contacts cell or casing directly	Short thermal path; strong uniformity potential	Dielectric-fluid compatibility and sealing
Refrigerant	Direct or coupled two-phase evaporation	Compact, high heat flux capability	Compressor/control complexity
PCM	Latent-heat buffering	Passive peak suppression	Finite capacity; regeneration required
Heat pipe	Two-phase passive heat transport	High effective conductivity; low parasitic power	Condenser heat rejection and orientation limits
Thermoelectric	Peltier heat pumping	Precise bidirectional control	Low coefficient of performance at high load
Hybrid	Combines complementary mechanisms	Balances peak buffering and sustained rejection	Added interfaces, controls and cost

3. Cooling Technologies

3.1. Air cooling

Air cooling remains the simplest active BTMS because it avoids coolant leakage and requires little hardware beyond ducts, fans, and flow-distribution features. Zhao *et al.* [7] reviewed air-cooled configurations and showed that the principal design challenge is not the nominal air-flow rate but the non-uniform distribution of that flow through a densely packed module. Channel taper, cell spacing, inlet position, and recirculation paths can therefore matter as much as fan capacity. The method remains attractive for moderate heat loads and cost-sensitive vehicles, but its low volumetric heat capacity makes it difficult to maintain small temperature spreads during sustained fast charging or high-power discharge.

Air cooling also illustrates why a thermal result must be interpreted over battery life rather than at one operating point. Chen *et al.* [8] compared air and phase-change-material cooling while considering cycle-life effects, showing that the apparent benefit of a cooling strategy depends on both peak temperature and thermal non-uniformity. In a direct comparison of air and liquid systems for a high-energy module, Akbarzadeh *et al.* [9] reported better temperature uniformity and energy efficiency for liquid cooling. The practical conclusion is not that air cooling is obsolete, but that its useful operating envelope is narrower as pack heat flux and fast-charge demand rise.

3.2. Indirect liquid cooling

Indirect liquid cooling is currently the most mature high-performance route for automotive packs. Heat is conducted from the cell through a cold plate, jacket, or thermal-interface layer and then carried away by a water-glycol or other coolant. Wang *et al.* [10] demonstrated the importance of module-level flow arrangement in a cylindrical-cell liquid system, noting that increased flow does not indefinitely improve cooling and that parallel flow paths can improve thermal balance. Akbarzadeh *et al.* [11] proposed a liquid cooling plate concept that further illustrates the central trade-off: enlarging contact and increasing coolant access generally improve heat removal, but they also increase mass, packaging demand, and hydraulic complexity.

Two recent reviews make the design trend clear. Zhao *et al.* [12] organized liquid-BTMS improvements around channels, jackets, cold plates, coolant choice, refrigeration coupling, heat pipes, and hybrid solutions. Wu *et al.* [13] extended this view by emphasizing multi-objective cold-plate optimization. The design target is therefore no longer simply the lowest Tmax. A credible liquid system must achieve low Tmax and ΔTmax at an acceptable pressure drop, with manufacturable channel dimensions and a flow distribution that remains stable across the intended operating range.

3.3. Direct liquid and refrigerant cooling

Direct cooling reduces the conduction path between the cell and working fluid. This includes immersion in a dielectric liquid and direct refrigerant evaporation at or near the battery surface. The thermal advantage is clear, but the system boundary becomes more demanding: coolant electrical properties, material compatibility, leakage detection, service procedures, and long-term sealing must all be controlled. Hong *et al.* [14] experimentally investigated direct two-phase refrigerant cooling and showed that the concept can satisfy cell-temperature limits under harsh conditions, while also demonstrating that vapor quality and two-phase state control strongly affect performance. Such systems are promising where very high heat flux justifies greater integration complexity.

3.4. Heat pipes and thermoelectric cooling

Heat pipes and vapor chambers transport heat with very low effective thermal resistance and negligible pumping power. Bernagozzi *et al.* [15] combined a loop heat pipe with graphite-sheet inserts and verified the concept using a numerical model and an experimental demonstrator. The device can spread heat efficiently, but the battery temperature still depends on how the condenser rejects heat to the environment. Heat pipes are therefore best viewed as heat transporters rather than complete heat sinks.

Thermoelectric cooling offers a different benefit: active, bidirectional temperature control without a circulating refrigerant loop at the cell interface. Cui and Hu [16] developed a robust predictive strategy around a thermoelectric cooler, illustrating the potential for combining thermal hardware with control. The limitation is efficiency. At high thermal loads, thermoelectric modules can consume substantial electrical power and generate additional heat at the hot side. Hybridization can mitigate this issue. Yao *et al.* [17], for example, studied a heat-pipe and refrigerant-based system coupled with the vehicle air-conditioning circuit, demonstrating how passive heat spreading and active heat rejection can be integrated.

3.5. Phase-change materials and hybrid systems

Phase-change materials (PCMs) absorb transient heat through latent heat and can suppress short temperature peaks without immediate auxiliary power. Their weakness is equally fundamental: once the phase-change capacity is exhausted, the PCM behaves mainly as a sensible heat store and must later be regenerated. For repeated fast-charge or high-load events, passive PCM alone is therefore insufficient. Xin *et al.* [18] investigated composite PCM combined with liquid cooling under high ambient temperature and rapid discharge, an architecture that separates transient buffering from sustained heat rejection. This functional separation is one of the most useful ways to interpret hybrid BTMSs.

4. Thermal-Hydraulic Design and Optimization

4.1. From temperature minimization to multi-objective design

A cooling design becomes physically meaningful when thermal benefit is evaluated together with the energy and packaging cost required to obtain it. Chen *et al.* [19] used multi-objective optimization and experimental investigation for a parallel liquid-cooled module under fast charging, reinforcing the need to treat Tmax and temperature uniformity as coupled design targets. Sui *et al.* [20] later optimized a hybrid-manifold liquid system with multiple objectives, illustrating the move from one-factor parametric sweeps toward Pareto-based design. For such studies, pressure drop or pumping power should be reported under a clearly stated flow boundary condition; otherwise an apparent thermal improvement can simply reflect an unaccounted increase in coolant throughput. The same caution applies to passive and hybrid devices. A heat pipe can show a low cell temperature while transferring heat to a condenser that is unrealistically cold, and a PCM can appear effective during a single discharge even though it is not regenerated before the next event. The heat-pipe review by Bernagozzi *et al.* [21] identifies these boundary-condition and system-integration issues as major barriers to broader EV adoption. The correct comparison is therefore between complete thermal pathways under equivalent duty, not between isolated components under unrelated laboratory conditions.

4.2. Evidence from recent liquid-cooling studies

Recent studies from Le Van Quynh and co-workers provide a compact progression from comparative cooling concepts to data-assisted optimization. Cong *et al.* [22] numerically compared two cooling-structure configurations for a lithium-ion battery pack, establishing the sensitivity of pack temperature to the geometry of the heat-rejection path. A subsequent pack-level thermal-efficiency study [23] compared two heat-dissipation models and provided a bridge between simplified cooling architectures and more detailed liquid-channel analyses. The influence of channel diameter and contact length was then examined explicitly [24], showing that solid-to-coolant contact geometry can be as important as coolant-side flow features.

At the channel level, Nguyen *et al.* [25] simulated liquid-channel cooling for an EV battery pack, while Cong *et al.* [26] compared three battery cooling models and reported how geometric parameters affect Tmax and ΔT. These studies are useful because they show the value of physically interpretable parameter screening before a high-dimensional optimizer is introduced. Geometry that has little influence should not consume expensive CFD samples, and improvements in temperature should be checked against the accompanying hydraulic penalty.

The later work moves directly into surrogate-assisted multi-objective design. Chau *et al.* [27] combined Gaussian-process regression (GPR) with NSGA-II for a serpentine channel and treated multiple thermal-hydraulic objectives simultaneously. In a related IEEE Access study, Chau *et al.* [28] developed a surrogate-assisted framework for serpentine liquid cooling and re-evaluated selected Pareto designs with the original CFD model. Cong *et al.* [29] extended the CFD-GPR-NSGA-II workflow to mini-channel cold plates, explicitly including maximum temperature, temperature difference, and pressure drop. This validation step is important because an optimizer can exploit small surrogate errors near the Pareto front if the predicted optimum is not returned to the high-fidelity model.

Coolant formulation is another design dimension. Ngoc *et al.* [30] investigated Al2O3 and CuO nanofluids in a serpentine liquid system, demonstrating that thermal performance can be modified through fluid properties as well as channel geometry. For vehicle application, however, any gain in convective heat transfer must be weighed against viscosity, pumping power, stability, fouling, material compatibility, and maintenance. The same thermal-hydraulic accounting used for geometry optimization should therefore be applied to advanced coolants.

Table 3: Representative evidence and the design lesson extracted for EV battery cooling.

Ref.	Cooling route	Study emphasis	Design lesson
[9]	Air vs liquid	Comparative thermal performance	Liquid cooling expands the usable high-load envelope.
[14]	Direct refrigerant	Two-phase cooling experiment	State control and sealing are part of thermal performance.
[18]	PCM + liquid	Hybrid transient buffering	PCM requires active regeneration for repeated duty.
[19]	Liquid cold plate	Fast-charge multi-objective design	Tmax and ΔT should be optimized together.
[20]	Hybrid manifold liquid	Multi-objective optimization	Hydraulic cost must accompany thermal gain.
[24]	Liquid block	Diameter and contact length	Solid-side contact geometry can dominate heat removal.
[27]	Serpentine liquid	GPR + NSGA-II	Surrogate models enable efficient Pareto search.
[28]	Serpentine liquid	Surrogate-assisted framework	Return selected designs to CFD for verification.
[29]	Mini-channel liquid	CFD-GPR-NSGA-II	Use thermal and pressure-drop objectives simultaneously.
[30]	Nanofluid liquid	Advanced coolant	Fluid enhancement must include viscosity and durability penalties.

5. Comparative Synthesis and Technology Selection

No single cooling technology is best for every electric vehicle. Air cooling is defensible where cost, simplicity, and leakage avoidance dominate and where the thermal load is modest. Indirect liquid cooling is the strongest general-purpose option for present high-energy and high-power packs because it combines controllable heat rejection with established automotive hardware. Direct liquid or refrigerant cooling can shorten the thermal path further, but only if fluid compatibility, dielectric safety, sealing, and control are addressed from the start. Heat pipes are effective heat spreaders and transporters, while PCM is valuable as a transient buffer; neither removes the need for a sink that ultimately rejects heat from the vehicle. Thermoelectric devices are most attractive when precise control or heating/cooling reversibility is more important than peak coefficient of performance.

The most useful selection question is therefore not "which method gives the lowest temperature?" but "which architecture maintains an acceptable thermal state over the required duty at the lowest system penalty?" For an urban EV with moderate charge power, a simple air or low-flow liquid system may be sufficient. For long-range vehicles and repeated fast charging, liquid cooling with chiller support or direct refrigerant integration becomes more credible. Hybrid PCM-liquid or heat-pipe-liquid systems become attractive when transient peak suppression is important, provided the passive element can be regenerated between events.

Table 4: Practical selection matrix for EV battery cooling systems.

Method	Thermal capability	Auxiliary energy	Implementation note
Air	Low–Med.	High	Compactness Med.; control Med.; maturity High
Indirect liquid	High	Med.	Compactness High; control High; maturity High
Direct/immersion	High	Med.	Compactness High; control High; maturity Developing
Refrigerant	High	Med.	Compactness High; control High; maturity Med.–High
PCM	Transient	High	Compactness Med.; control Low; maturity Medium
Heat pipe	Med.–High	High	Compactness High; control Low–Med.; maturity Medium
Thermoelectric	Medium	Low	Compactness High; control High; maturity Low–Med.
Hybrid	High	Med.	Compactness Med.; control High; maturity Developing

6. Research Gaps and Future Directions

First, cooling systems should be evaluated over realistic operating sequences rather than isolated steady points. Fast charging followed by urban driving, repeated acceleration events, hot-soak conditions, and cabin cooling demand can change coolant temperature and available chiller capacity. A design optimized at one inlet temperature and one flow rate may therefore be fragile when installed in a vehicle.

Second, thermal and hydraulic models need more complete validation. Temperature-only validation is insufficient for a liquid cold plate whose geometry directly changes flow distribution and pressure loss. Future studies should report inlet and outlet pressure, flow rate, representative cell temperatures, and an energy balance. For surrogate-assisted optimization, cross-validation error should be supplemented by high-fidelity re-evaluation of selected Pareto designs and, where possible, experimental confirmation.

Third, passive and hybrid systems require explicit recovery metrics. For PCM, useful quantities include melt fraction after the thermal event and solidification time before reuse. For heat pipes, condenser-side rejection and start-up behavior should be reported. These metrics determine whether a promising single-cycle result can survive repeated vehicle duty.

Finally, the next design step is vehicle-level co-design. Cold-plate geometry, coolant flow scheduling, chiller set-point, cabin HVAC demand, pump and compressor efficiency, battery ageing, and safety constraints should be considered together. This does not mean every study must model a complete vehicle. It means that component optimization should use boundary conditions and objective functions that are consistent with the system in which the component will operate.

7. Conclusions

Battery cooling for electric vehicles has evolved from a choice between air and liquid cooling into a broader thermal-management problem that includes transient buffering, passive heat transport, refrigerant integration, advanced coolants, and data-assisted optimization. Air cooling remains useful for moderate loads and simple packaging. Indirect liquid cooling is the most mature high-performance architecture, while direct liquid and refrigerant systems offer a shorter thermal path at the cost of greater sealing and control demands. PCM and heat pipes can improve transient behavior, but their benefit depends on a credible route for heat rejection or regeneration. Thermoelectric cooling provides precise control but remains constrained by efficiency at high load.

Across all architectures, the strongest design criterion is not the minimum temperature obtained in one simulation. A robust BTMS should maintain acceptable Tmax and ΔTmax while limiting pressure drop or auxiliary energy, mass, volume, and implementation complexity. Recent CFD-surrogate-optimization studies show how these competing objectives can be treated systematically, but high-fidelity and experimental verification remain essential. Future progress is therefore likely to come from co-design of cooling hardware and operating strategy under realistic charging, driving, ambient, and vehicle-HVAC conditions.

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