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Review and Analysis of Heat Dissipation Methods for New Energy Battery Systems in Electric Vehicle

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Abstract. Effective thermal management is pivotal to the performance, safety and lifetime of lithium-ion traction batteries in electric vehicles. This review synthesizes mainstream and emerging heat-dissipation strategies like forced air, indirect liquid cold plates, phase-change materials (PCMs), thermoelectric (TEC) assistance, and two-phase devices such as heat pipes and oscillating heat pipes, then compare them across heat-removal capacity, temperature uniformity (ΔT), energy overhead, packaging complexity, and safety. Evidence shows that natural convection is inadequate for large cells and well-designed forced air can serve moderate C-rates but often leaves persistent non-uniformity. Indirect liquid cooling provides tighter temperature control and scales to fast-charge duty when manifold balance and thermal interfaces are optimized. PCMs excel at transient peak shaving and uniformity but require a recharge path; TECs deliver precise, bidirectional hot-spot control at the cost of electrical power and robust hot-side rejection. Passive two-phase spreaders efficiently relocate heat and suppress gradients when properly integrated. The analysis supports hybrid battery thermal-management systems that combine liquid plates for baseline control, passive spreaders for isothermalization, and selectively engaged boosters (PCM/TEC) coordinated by intelligent control. Such integrated designs are most likely to maintain 20–40 °C operating bands, hold cell-to-cell ΔT < 5 °C, and reduce runaway risk while minimizing lifecycle cost in next-generation EV packs.

Keywords: Battery thermal management, Electric vehicles, Air cooling, Liquid cooling

1. Introduction

With the increasing adoption of electric vehicles (EVs) as a response to the global environmental crisis and the depletion of fossil fuels, lithium-ion batteries have become the preferred power source due to their high energy density, long lifespan, and reliability. However, the efficiency, safety, and lifespan of these batteries are heavily influenced by their operating temperature. Temperature variations within batteries during charge and discharge cycles can lead to performance degradation, reduced lifespan, and even thermal runaway, which poses serious safety risks [1, 2]. The battery management system (BMS) has become a critical component in the design and operation of electric vehicles. The need for effective thermal management within lithium-ion battery systems has become paramount as battery temperature directly affects its cycle life, charge retention, and safety. In fact, improper temperature control may result in the battery's premature failure, loss of capacity, and

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catastrophic events such as fires or explosions. As such, there is a growing emphasis on developing methods to manage the heat generated during the battery's operation. Effective thermal management is crucial for optimizing the performance and lifespan of lithium-ion batteries. Overheating, particularly in high-power applications such as electric vehicles, accelerates the degradation of key battery components, including the electrolyte, electrodes, and separators. This has led to significant research into various cooling strategies aimed at mitigating these issues [3]. In this paper, we review and analysis the current state of heat dissipation technologies used in EVs battery systems, focusing on both active and passive cooling methods, and highlight the improvements and challenges faced in battery thermal management [4].

2. Mainstream battery cooling methods

2.1. Air cooling

Air cooling is one of the simplest and most cost-effective cooling methods. It can be classified into natural convection and forced convection systems [2]. In natural convection, ambient air is used to dissipate heat without any external power source, while forced convection systems employ fans or blowers to enhance airflow around the battery pack. Considering the cost and space limitation, the forced air cooling is widely used as the cooling method of battery pack at home and abroad [3]. Its efficiency depends on duct topology, entrance and exit placement, shape and pack arrangement like serial and parallel airflow paths [2, 5] as shown in Figure 1.

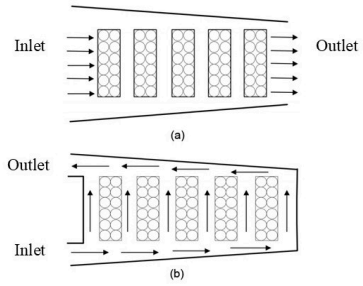

Figure 1. A. series wedge channel; b. u-shaped parallel channel [5]

Experiments and 2-D transient models show natural convection is inadequate for large cells; forced convection lowers average temperature but often leaves nonuniform temperature distribution due to local heat transfer coefficient (h) disparities and core conduction bottlenecks. The same cylindrical Li-ion cell reached 47 °C under natural convection and 33 °C under forced air as shown in Figure 2 [1].

In a forced-air study on a 48-cell pack (2 parallels and 6 series model), transitioning from longitudinal to horizontal arrangement shortened flow paths and improved cooling but still struggled at high loads. Adding a bottom duct leveraged conduction area and top-side natural convection; replacing a double “1” with a double “U” duct further lowered maximum temperature rise and ΔT across environments. At 20°C ambient and 1C rate, the double-u” lowered ΔT by 24% in comparison with double “1” (3.29°C and 4.34°C) and the maximum temperature rise to 10.10°C, as shown in Table 1 [3].

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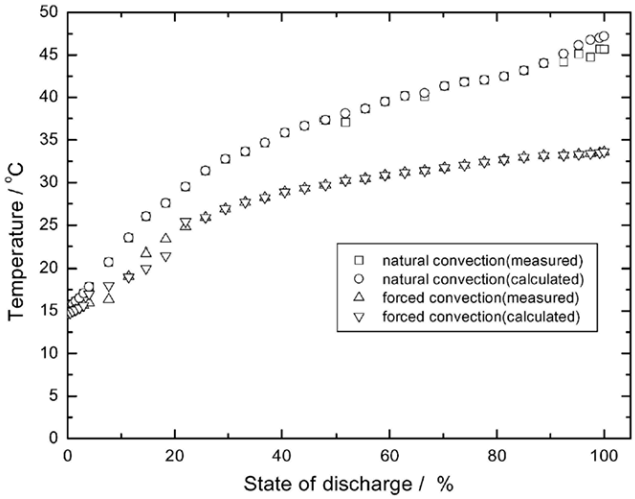

Figure 2. Measured and calculated surface temperatures under natural and forced convection [1]

Table 1. When environmental temperature is 20 °C, the comparisons of heat flow field characteristics with different bottom airflow ducts [3]

	The double "1" type duct	The double "U" type duct
Flow rate(m^3/h)	7.26	7.44
The maximum temperature rising (°C)	10.36	10.10
The maximum temperature difference (°C)	4.34	3.29
Pressure drops (Pa)	60	62

The primary advantage of air cooling is its low cost and simplicity. It also does not require complex sealing or additional maintenance, making it an attractive option for small-scale applications. However, the efficiency of air cooling is limited, especially when the battery operates at high power levels or in warm environments. Air cooling systems may also fail to maintain uniform temperature distribution, leading to thermal hotspots within the battery pack [5]. This is the reason that air cooling is typically used in low-power applications or as a supplementary cooling method. Air cooling also has limitations in large-scale applications, especially where higher energy densities and more significant thermal loads exist [5].

2.2. Liquid cooling

Liquid-based thermal management systems for batteries can generally be classified into two categories. The first distinction is whether the coolant is in direct physical contact with the battery surface or whether heat transfer occurs indirectly through an intermediate structure. Another classification depends on the control strategy of the system, which may operate in either a passive or an active mode. Passive liquid cooling offers only limited temperature regulation and low heat dissipation efficiency, making it suitable primarily for battery packs with relatively low power output. By contrast, active liquid cooling has attracted significant attention both in research and industrial practice. Indeed, leading manufacturers such as Tesla and General Motors have widely implemented active liquid cooling systems in their commercial electric vehicles, highlighting its superior capability in ensuring effective thermal management [6].

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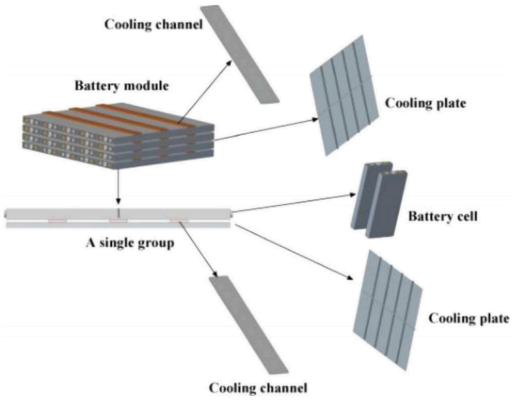

Figure 3. Liquid-cooled battery thermal management model using rectangular flow channels and cold plates [6]

Liquid plates offer higher heat capacity and heat-transfer coefficients than air, enabling tight control of both absolute temperature and uniformity at pack scale. Performance depends on channel geometry, manifold balance, coolant selection and thermal interfaces. Studies identify for the model as shown like fig. 6 the dominant factors are the number of channels and refrigerant flow. At the same time, height and width of channels are secondary factors. For example, with 4 channels at 0.07 m/s flow rate and 45 mm width × 5 mm height, both mean temperature and temperature difference were minimized. Flow-distribution management via manifold redesign like T-joint improves module-to-module uniformity. For a 2C discharge at 36 L/min, maximum temperature is 312 K and the temperature difference is 11 K. The literature emphasizes that future liquid designs should target not only peak temperature suppression but also standard temperature deviation across cells as shown in Figure 3 [6].

Liquid systems add mass, sealing and integration complexity but they remain the most robust for high-load operation and fast charging when uniformity and headroom are paramount [6].

2.3. Phase-Change Materials (PCM)

Phase-change-material (PCM) thermal management for traction batteries exploits latent heat near the selected melting range to attenuate transient peak temperatures and improve inter-cell uniformity during fast charging or intermittent high-load events; because PCMs are not steady-state heat sinks, they must be hybridized with an ultimate rejection path like air, liquid, or direct-refrigerant to “recharge” between events [1, 2].

Engineering practice typically addresses four aspects: 1. Melting-range selection close to the pack control set-point so latent absorption is available when needed without penalizing cold-weather warm-up [3]. 2. Thermal-conductivity enhancement of low-k bases via expanded graphite, metal foams, graphene or CNT networks to reduce through-plane and in-plane resistances while providing structural integrity [4, 5]. 3. Leakage control and form stability through shape-stabilized composites often combined with flame-retardant additives to strengthen safety margins [7, 8]. 4. Pack-level integration tailored to cylindrical, prismatic or pouch modules to minimize contact resistance while preserving electrical isolation and manufacturability [9]. PCMs are best deployed as a passive buffer layer within a hybrid BTMS, delivering peak shaving and uniformity gains with minimal parasitic power when coupled to air, liquid, direct-refrigerant sinks and intelligent control which is particularly valuable for fast charging and intermittently aggressive duty cycles [2, 4, 9].

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2.4. Thermoelectric (TEC/Peltier) cooling

Thermoelectric cooling uses the Peltier effect in semiconductor p–n couples to pump heat roughly in proportion to the drive current. For traction batteries that translates into two appealing traits: precise, fast local control and a compact, modular form factor. Within the broader BTMS taxonomy—air, liquid, direct-refrigerant and newer passive/two-phase routes—TECs sit as a device-level option often discussed alongside heat pipes and PCM in the "new BTMS" toolkit for EVs [10].

In real packs, TECs are rarely standalone. They're sandwiched between the cell surface and a secondary sink so that both the moved heat and the Joule losses are cleanly rejected. A typical stack runs: cell can/base → thin, low-resistance TIM → TEC module → lateral spreader → air or liquid sink. Demonstrator systems in EV research follow this hybrid recipe, pairing TECs with a liquid loop and forced air on the hot side to stabilize cell temperatures while keeping electrical parasitics within sensible budgets [7]. This strategy matches review conclusions that advocate coupling multiple cooling modes at the pack level to boost heat removal and tighten temperature uniformity versus single-mode designs [8].

The performance signature of TEC-assisted cooling is selective hot-spot suppression and intra-module uniformity improvement, rather than bulk steady-state heat removal. At large temperature lifts and high heat flux, effective efficiency degrades, and the hot-side sink can become the limiting element. Therefore, TECs are best positioned as trim actuators layered over an air or liquid baseline. This positioning is consistent with broader BTMS evidence: forced convection alone can leave persistent surface non-uniformity and hot spotting in large cells and packs, so a localized actuator that works at the solid interface is advantageous. Contemporary surveys that benchmark thermoelectric element-based BTMS similarly frame TECs as precise, local controllers that complement the primary sink, particularly under fast-charge or pulsed-load events where cell-to-cell ΔT must be held within tight bounds [9].

2.5. Heat pipes and oscillating/pulsating heat pipes (OHP/PHP)

Heat-pipe–based battery thermal management relies on passive, two-phase transport to deliver very low thermal resistance between cell hot spots and a remote sink, and has matured from classical wicked heat pipes and loop/flat variants to wickless oscillating (pulsating) heat pipes (OHP/PHP) and micro heat-pipe arrays tailored to EV pack geometries; by relocating heat out of dense cell clusters and equalizing surface fields, these elements suppress peak temperature and shrink intra-module gradients when properly coupled to a condenser on the hot side. System-level reviews document heat pipes as an efficient element class for BTMS—with reported deployments spanning sintered and loop pipes, OHP/PHP, and MHPA plates—and emphasize their role in reducing cell-to-cell ΔT while leveraging either air or liquid sinks at the condenser end [9]. Practical integration details strongly govern outcomes: in early experiments on large cylindrical cells, forced air alone lowered average temperature yet left axial non-uniformity; a poorly bonded heat pipe showed little benefit, whereas embedding the pipe into finned condensers and adding a small fan both reduced absolute temperature and essentially eliminated positional non-uniformity—clear evidence that interface quality and condenser design dominate realized performance [1]. Contemporary work differentiates wickless OHP/PHP from conventional pipes: a serpentine, multi-turn capillary loop sustains self-excited slug/bubble oscillations that move substantial sensible heat without wicks, with capacity tunable by turn count; EV-oriented studies further show that OHP condensers can be air- or water-cooled, and that coupling OHP with PCM improves transient handling versus OHP alone. Beyond rigid copper or steel constructions, flexible OHPs have been demonstrated for space-

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constrained routing inside packs, where adiabatic-section length and bending radius measurably affect start-up and overall thermal resistance; small-bend layouts maintain acceptable performance and keep evaporators within desired ranges in EV-like power inputs. Mounting micro heat-pipe arrays beneath prismatic modules lowers temperature rise rates and tightens spatial uniformity during charge–discharge cycling which is a clear evidence that two-phase spreaders can bridge the gap between cell-core heat generation and the primary sink [9]. A complementary line of work pairs heat pipes with PCM: the pipe's high effective conductivity widens the usable PCM melt window and helps pull stored heat back to the sink between events, yielding lower peaks and smaller ΔT than PCM alone under aggressive duty. Multiple demos show PCM–HP hybrids can meet EV-relevant limits when the condenser is sized correctly. Finally, closed-loop or oscillating heat-pipe modules have also been used on the heating side for cold-weather operations showing that with suitable fluids, geometry, and controls, two-phase devices support bidirectional thermal management at sub-zero start-up. In short, heat pipes and OHP/PHP act as passive, high-conductance spreaders whose payoff depends on interface quality and condenser capacity.When they are paired with air or mini-channel liquid sinks they form a lightweight, effective layer for hot-spot suppression and uniformity control in modern EV packs [9].

3. Analysis

3.1. Performance

Forced-air cooling can be workable at moderate C-rates but it runs into a hard limit set by air's low heat capacity. In practice, duct topology beats brute fan power: moving from longitudinal to horizontal flow shortens the path; adding a bottom duct increases the conduction contact area; swapping a "double-1" for a double-U loop drops both peak temperature rise and ΔT. Even so, at 1C and 20 °C, simple horizontal layouts missed the design targets, whereas the bottom-duct + double-U configuration "basically met" them—evidence that performance is tied far more to geometry than to raw airflow [3].

Heat pipes transport heat with little parasitic draw and noticeably smooth hot spots when slipped between cells. Large and flexible oscillating heat pipes have held evaporators below 50 °C under tens of watts and both placement and the adiabatic section length are pivotal. In side-by-side tests, OHPs cut cell-to-cell temperature spread much more than bare air or plate-only baselines [6].

PCMs shine at transient peak shaving and uniformity: latent heat near a tuned melting range soaks up spikes during acceleration or fast charge. On their own, PCMs are not a steady heat sink since they must be "recharged" by a coupled loop to remove stored heat between events. Composite PCMs improve conductivity and form stability to control leakage while preserving dielectric safety. Hybrid PCMs and active systems repeatedly demonstrate lower peaks and better ΔT at minimal extra power, especially valuable in intermittently aggressive duty cycles [9].

Thermoelectric (TEC/Peltier) modules deliver fast, bidirectional control and precise set-point tracking. A lab system combining TECs with loops showed 43 °C surface drop for a single cell case, evidencing strong spot-cooling potential. The trade-off is electrical power draw and heat rejection on the hot side. This makes TECs most compelling as targeted add-ons rather than sole pack-wide solutions [7].

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3.2. Engineering suitability

Air systems win on simplicity, weight, and cost—no seals, no coolant—making them attractive for low-power packs or as secondary rejection paths. But meeting high load or hot-soak conditions demands carefully engineered ducts, which adds design effort without changing air's fundamental thermal limits [3].

Liquid plates add mass, plumbing, sealing, and manifold design challenges. Yet, they scale cleanly to high power and fast charge, work across cell formats, and enable tight thermal control if flow distribution and thermal interfaces are well managed. Microchannel design and composite plates can lower peak temperature with low pumping fractions, indicating good system efficiency when co-designed with the pack [9].

Heat pipes are compact and passive, well-suited to tight battery bays and module interstices. Their effectiveness is geometry dependent. Flexible polymer and fluor rubber OHPs offer packaging adaptability but require careful routing to avoid performance-killing bends, and condenser sections still need an ultimate sink [6].

PCMs pack neatly around cells and add little to the control or plumbing side. The real work lies in materials tuning: raising effective conductivity, improving flame retardancy, and stabilizing shape to prevent slump or leakage. Because a PCM stores heat rather than rejecting it to ambient, it acts as a system buffer instead of a sink. When coupled to an air or liquid loop, a thin PCM layer clips transients and trims cell-to-cell ΔT without upsizing blowers or pumps [9].

Thermoelectric modules are compact and easy to tile but they draw electrical power directly and need a well-engineered hot-side path. They make the most sense where tight, localized temperature regulation outweighs the energy penalty [7].

3.3. Safety and reliability

Uneven temperature fields accelerate aging and nudge cells toward conditions where thermal runaway is more likely. The most reliable way to widen safety margins is to suppress ΔT at its origin rather than react downstream. In air-only packs, stubborn hot spots remain even with strong forced convection which is why design rules often prioritize duct topology and cap the allowable C-rate. Early EV results showed that natural or forced convection over bare cells still produces surface gradients that are hard to govern once scaled to full packs. But pairing airflow with fins and heat pipes lowers the temperature rise and smooths the map, this is a practical signal that bulk air alone needs help [1].

Liquid cooling trades performance for new hazards which are leakage paths and the need for electrical isolation. Better seals and dielectric coolants limit those risks but they cost mass, money, and packaging volume. PCM bring their own issues like flammability and seepage. Oscillating heat pipes are passive and electrically quiet and they are sensitive for geometry and orientation.Their long-term stability hinges on maintaining slug and plug oscillations across the duty cycle. Thermoelectric modules are solid-state but if its control is sloppy or heat rejection is undersized, they pile heat onto the condenser side and negate the benefit [6, 9].

4. Conclusion

Air cooling that used on its own rarely meets the needs of today's high–energy-density battery packs. Natural convection cannot keep large-format cells within safe limits and even carefully engineered forced-air designs tend to leave pockets of temperature non-uniformity that complicate

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state estimation, aging behavior, and safety logic. The adjustments to duct geometry and inlet–outlet placement can shorten flow length and smooth the distribution but will still struggle under heavy loads or warm ambient conditions. This pattern shows up consistently from early cell-level tests through pack-scale CFD and bench experiments.

The most effective levers are increasing the heat-transfer coefficient and spreading heat laterally. Indirect liquid cold plates hold tighter absolute temperatures and smaller cell-to-cell ΔT than air systems at comparable packaging volume. Heat pipes with oscillating and pulsating designs and flexible formats provide lightweight and passive isothermalization between neighboring cells. Experiments keep evaporators below 50 °C at moderate loads and tolerate bends with appropriate design and directly attacking hot spots and limiting gradients that drive imbalance. Hybrid schemes extend this envelope that liquid–air combinations and thermoelectric assistance allow TEC-aided indirect-liquid systems to pull surface temperatures down rapidly with manageable power for short "boost" events and turning off during cruise to conserve energy.

Thermal management must also work in the opposite direction. Cold-weather operability is as important as high-temperature safety. Pulsating heat-pipe modules which used for pre-heating and heat retention reduce the voltage sag, raise the deliverable capacity below 0 °C, and keep the surface ΔT within a few degrees which showing that the same capillary–inertial mechanisms used for cooling can be repurposed for efficient heating.

Gathering these results together with the broader literature the most actionable constraints remain the operating band of roughly 20–40 °C and a cell-to-cell ΔT target below 5 °C. When temperatures are above 80 °C the runaway risk and aging rates are sharply increased. A robust path forward is an integrated hybrid BTMS with indirect liquid plates for baseline control, passive spreaders for uniformity, and selectively engaged active boosters for transients. They work together and cooperate with model-predictive control that links electro-thermal states to health and safety limits.

Practically, the three guidelines are: (i) prioritizing uniform flow in ducts and plate manifolds before sizing capacity. (ii) placing passive spreaders where structural gaps and edge cells that tend to overheat. (iii) implementing bidirectional strategies tuned to ambient conditions and duty cycle. Systems built this way are more likely to deliver durable performance, larger safety margins and lower lifecycle cost for next-generation EV packs.

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