

Battery Thermal Management Systems for Electric Vehicles: A Review of Liquid Cooling and Mist-Assisted Approaches

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Abstract- Lithium-ion batteries generate heat during charge and discharge, and their performance, ageing and safety depend on temperature and temperature uniformity. This review synthesizes foundational and recent literature on battery thermal management systems (BTMS), with emphasis on indirect liquid cooling, serpentine and microchannel passages, and evaporative mist cooling. The literature shows that cooling performance depends on the battery heat load, cell-to-coolant thermal contact, channel geometry, coolant conditions, heat-exchanger capacity and auxiliary power. Serpentine channels can improve heat transfer coverage, but their hydraulic resistance and pumping demand must be considered alongside peak temperature and cell-to-cell temperature spread. Mist cooling can add evaporative heat rejection, while its outcome depends on humidity, airflow, droplet evaporation and water carry-over. Findings from the two papers central to this project—a 2024 mist-cooling study and a 2026 serpentine microchannel experiment—are therefore interpreted within their own test boundaries rather than treated as direct performance forecasts. The review applies this synthesis to a proposed laboratory system using a copper serpentine-tube liquid loop and optional mist introduced at the radiator air inlet. Since assembly and testing are pending, the manuscript reports no experimental result for that system. It recommends matched test cases and combined thermal, hydraulic and electrical measurements to establish whether additional cooling justifies pump, fan and mist-system energy use.

Keywords: battery thermal management; electric vehicles; lithium-ion batteries; serpentine cooling; microchannel; mist cooling; auxiliary energy

I. INTRODUCTION

Battery thermal management is a vehicle-level engineering problem because heat generated in cells must pass through cell casings, interfaces, cooling hardware and ultimately to the environment. Internal resistance and electrochemical processes generate heat during operation; the resulting temperature field depends on current, state of charge, cell design, ageing and boundary conditions. Early thermal analyses and later reviews emphasize that a useful BTMS must manage both the absolute temperature and spatial non-uniformity across cells, while remaining compatible with the manufacturer's operating limits [1, 2, 6, 7].

A high average module temperature can accelerate degradation, while a local hot region can create uneven ageing and reduce the thermal margin of the pack. Low temperatures also affect power delivery and charging behavior. As a result, a design should be evaluated using several instrumented locations, not a single

temperature reading, and should be assessed under documented load and ambient conditions [1, 6, 8]. Published temperature targets vary with chemistry and cell format, so this review does not prescribe one universal operating window.

The field includes air cooling, indirect liquid cooling, direct immersion, phase-change materials (PCMs), heat pipes, refrigerant-based systems, thermoelectric devices and hybrid combinations. Reviews identify liquid cooling as a practical option for larger heat loads because it can transport heat from a module to a remote heat exchanger. That advantage comes with plumbing, sealing, pump energy and control requirements [5–8]. Mist cooling uses evaporation to enhance heat transfer, but implementation and safety depend on where water is introduced and whether droplets evaporate before reaching electrical components [4, 9].

This paper reviews the thermal-management literature in the context of a laboratory project whose proposed

apparatus combines a copper serpentine-tube cooling interface, a pump-driven coolant loop, radiator and fan, and a controlled mist supply directed toward the radiator air inlet. The intent is to connect published design principles to a testable system boundary while keeping reported literature outcomes separate from the not-yet-measured performance of the proposed apparatus.

II. REVIEW SCOPE AND APPROACH

This manuscript is a focused narrative review, not a systematic review or meta-analysis. It draws on the two research papers supplied for the project, foundational thermal-management work, recent review articles, and selected experimental or numerical studies on serpentine liquid cooling, mist cooling, hybrid plates and drive-cycle performance. The literature considered spans 2002–2026. Papers were selected for relevance to cell heat generation, cooling architecture, channel design, evaporative cooling, system-level energy use and experimental evaluation. Because cell formats, heat loads, environmental conditions and measurement boundaries differ substantially, quantitative outcomes are reported with their study conditions and are not pooled into a single ranking.

The review has three linked aims: (i) summarize how battery thermal needs shape cooling-system selection; (ii) compare the strengths and constraints of liquid and mist-based approaches, especially serpentine cooling; and (iii) identify measurements needed to evaluate a laboratory-scale copper-tube loop with radiator-side mist. Search and selection details are intentionally described at this level because no reproducible database-by-database search protocol or formal screening log was provided in the source synopsis.

III. BATTERY HEAT GENERATION AND PERFORMANCE REQUIREMENTS

Battery heat generation is not constant through a test. Resistive losses and electrochemical heat vary with current, voltage, state of charge, temperature and the changing condition of the cell. Thermal models therefore require electrical and thermal inputs, and comparative tests should record the applied load and starting state [1, 2]. A run with higher current or warmer ambient air can show a higher cell temperature even when its cooling hardware is unchanged.

Four measurement groups are particularly important. First, maximum measured cell temperature, $T_{\max}$, tracks the hottest instrumented point. Second, the measured spread, $\Delta T_{\text{cell}} = T_{\max} - T_{\min}$, describes temperature uniformity across the selected sensors. Third, coolant inlet and outlet temperatures together with mass flow rate can estimate heat pickup across the cooling section. Fourth, electrical energy used by pumps, fans and actuators helps determine the cost of the thermal benefit. These measurements should be aligned in time and interpreted within the same system boundary [2, 6, 11].

The phrase ‘cooling efficiency’ can obscure trade-offs. A lower $T_{\max}$ may require greater coolant flow and pump power, while a fan or mist pump may add further demand. Thermal performance should therefore be reported together with pressure loss, accessory power or energy, coolant use and relevant ambient conditions. A project-specific benefit-per-energy indicator can aid comparison, but it should be explicitly defined and should not be presented as a universal BTMS standard or thermodynamic efficiency unless a complete energy balance supports that label [5, 11].

IV. OVERVIEW OF BATTERY THERMAL MANAGEMENT STRATEGIES

BTMS approaches differ in their heat-transfer medium, active energy demand, packaging and control requirements. Air systems are mechanically simple and can suit lower heat loads, but air's heat capacity and convective transfer capability can limit performance in compact modules. Indirect liquid systems move heat through a conductive interface into a coolant channel; they offer controllable heat transport but introduce pumps, seals, hoses and auxiliary demand. PCMs provide transient thermal buffering through latent heat, but their capacity is finite and thermal regeneration is required. Heat pipes transport heat passively over a distance, though integration and contact design remain important. Direct immersion can improve contact between cells and coolant but requires dielectric-fluid compatibility and careful electrical/material qualification [6–8, 14–17].

Mist cooling is an evaporative method. When droplets evaporate, latent heat is absorbed from the surrounding air or target surface. The thermal effect depends on the water flow and droplet size, air

movement, temperature and relative humidity. Hybrid systems can combine an active heat-removal path with thermal storage or another heat-transfer mode, but they also add control and validation complexity [4, 9,

13, 16, 17]. Table 1 summarizes the practical trade-offs most relevant to the reviewed studies.

Table 1. Qualitative comparison of BTMS approaches based on the reviewed literature [5–9, 13–17].

Approach	Potential strengths	Main constraints	Relevance to this review
Forced-air cooling	Simple layout; low-cost components	Limited heat transport at high load; possible flow-related non-uniformity	Useful as a safe reference or baseline case
Indirect liquid cooling	High heat-capacity fluid; controllable heat transport; scalable interfaces	Pump energy, pressure drop, leaks, contact resistance and sealing	Core architecture of the proposed serpentine-tube loop
PCM / hybrid plate	Buffers transient heat; can reduce temperature peaks	Finite storage, low conductivity unless enhanced, added mass and regeneration needs	Comparison category; not assumed in the core test
Immersion cooling	Direct fluid contact can improve heat transfer	Dielectric-fluid qualification, material compatibility and enclosure complexity	A distinct design class from indirect copper-tube cooling
Mist / evaporative cooling	Latent heat can increase air-side or surface heat rejection	Humidity dependence, droplet carry-over, water management and electrical wetting risk	Project mist is proposed at the radiator air inlet only

V. LIQUID COOLING AND SERPENTINE CHANNEL DESIGN

In an indirect liquid system, heat conducts from a cell or module through an interface into a plate, tube or jacket. The coolant then carries heat to a heat exchanger. The cooling result is shaped by the thermal contact, wetted area, channel geometry, coolant properties, inlet temperature, mass flow rate and heat-exchanger capacity. Increasing flow can improve convective transfer, but it also increases pressure loss and pump demand; therefore, geometry and operating point should be optimized against multiple objectives rather than maximum heat transfer alone [5, 11].

Serpentine routing distributes a continuous flow path across the cooling surface and can increase the length of contact between coolant and the module interface. Bends and longer paths can also increase hydraulic resistance, and coolant warming along the channel can create spatial temperature variation. Deng, Zhang and

Ran numerically compared channel layouts for a rectangular cell. In their model, a five-channel layout along the cell length produced a maximum-temperature reduction of up to 26 °C relative to a two-channel arrangement along the width. This result demonstrates the influence of layout within that modeled geometry; it is not a transferable temperature reduction for another plate, tube or battery [3].

The 2026 experimental study by Khoharo and colleagues is a close comparator because it tested a 20-cell, 21,700-format module with a serpentine microchannel-tube cooling design. The authors tested 1C, 2C and 3C charge/discharge conditions and flow rates from 100 to 700 mL/min. At 1C and a reported optimal flow rate of 300 mL/min, the study reported a temperature decrease from 57 °C to 37 °C; it also reported greater reductions at higher discharge rates under its tested conditions [10]. Those values belong to the article's 42 V module and test arrangement. They should guide questions about instrumentation and test design, not serve as a performance target for a copper

tube with different cell count, contact area, coolant, radiator and ambient conditions.

Other work broadens the design space. Numerical and review studies examine cold-plate layout, channel dimensions, coolant and optimization criteria [5, 7]. Experiments and models also consider coupled air/liquid plates, microchannel/PCM hybrid plates, dielectric immersion cooling and heat-pipe/fin hybrids [12–16]. These studies reinforce two points: performance is configuration-specific, and a complete BTMS has to be evaluated beyond the cooling channel itself. Battery-to-interface contact, radiator heat rejection, pressure drop, electrical isolation, fan conditions and accessory energy all influence system outcomes.

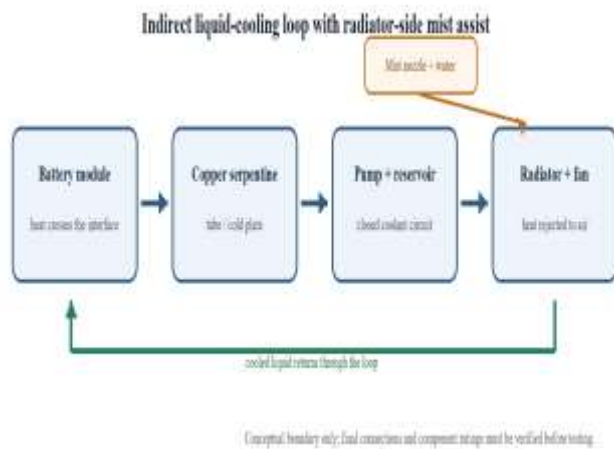


Figure 1. Review synthesis of the proposed indirect liquid loop. The mist nozzle is shown on the radiator air side and is not directed at the battery or electronics.

1. Mist And Evaporative Cooling

Mist cooling uses the evaporation of fine droplets to absorb latent heat from air or a surface. It can enhance air-side cooling without circulating a second liquid through the battery interface, but its performance depends on whether droplets evaporate, how the air stream carries them and whether water reaches sensitive surfaces. Water quality, nozzle characteristics, flow rate, humidity and drainage therefore form part of the system design rather than being secondary operating details [4, 9].

Saw and colleagues combined experiments and validated numerical modeling to study mist cooling of lithium-ion battery packs. Their work reported improved temperature distribution relative to dry-air cooling in the investigated configuration; the paper's module-level simulations found that a specified mist loading and flow condition could keep modeled surface temperature below 40 °C. The result is tied to their modeled pack and operating conditions, and their direct mist approach differs from a radiator-side nozzle [4].

Teranishi and colleagues investigated an impinging mist-jet BTMS for hybrid electric vehicles. Their experiments and simulations reported complete evaporation under the selected dilute-mist conditions and a cooling effect of up to 7.4 K in their test system [9]. Complete evaporation matters because residual water on a battery or electrical assembly may create corrosion or electrical risks. The reported cooling effect should not be assumed for a radiator spray: the target surface, airflow path and heat-transfer boundary are different.

For the proposed prototype, mist is described as an optional air-side enhancement at the radiator inlet, while the battery remains cooled indirectly by a closed liquid loop. This separation may reduce the likelihood of wetting the cells, but its benefit is uncertain until measured. A radiator-side mist test should record air temperature and relative humidity upstream of the spray, coolant inlet/outlet temperature, radiator airflow, water consumption and electrical demand. Trials should be stopped or excluded if droplets carry over to electrical equipment or condensation cannot be controlled.

2. Cross-Study Evidence And Limits Of Comparison

Table 2 compares selected studies that inform the present topic. It places numerical and experimental results beside their test boundaries to prevent a direct ranking of unlike designs. A reported temperature reduction can change with cell format, discharge rate, cooling surface, coolant flow, ambient condition, measurement location and whether the result comes from a physical experiment or a validated model.

Table 2. Selected findings and their transferability limits [3, 4, 9–11].

Study	Method and configuration	Reported result	Interpretation for this review
Deng et al. (2018) [3]	Numerical serpentine cold plate for a rectangular Li-ion cell	Up to 26 °C lower maximum temperature for one modeled layout versus another	Evidence that channel number and direction matter; not a prototype forecast
Saw et al. (2018) [4]	Dummy-cell experiment with model-based pack evaluation of mist cooling	Mist cases improved module temperature distribution in the studied setup	Direct mist results depend on mist loading, airflow and modeled boundaries
Vikram et al. (2022) [11]	MATLAB/Simulink liquid-BTMS study under Indian and FTP-75 drive cycles	Compared coolant options, ambient conditions and BTMS energy in a drive-cycle model	Shows why drive/load and accessory energy belong in the system boundary
Teranishi et al. (2024) [9]	Experimental and numerical impinging-mist BTMS for HEVs	Up to 7.4 K cooling effect; complete evaporation under selected conditions	Supports humidity/evaporation monitoring; radiator-side mist is a different arrangement
Khoharo et al. (2026) [10]	Experimental 20-cell 21,700, 10S2P module with serpentine microchannel tube	At 1C and 300 mL/min, 57 °C to 37 °C was reported in their test	Closest serpentine experimental comparator; hardware and loads must be matched before comparison

Drive-cycle simulations, bench experiments and CFD answer different questions. Numerical work can isolate design variables, while experiments reveal contact resistance, leaks, sensor placement and other build-dependent effects. A credible comparison should state the model's validation basis or report the physical test's cell count, load, flow, ambient condition and sensor locations. Published results should be used as design evidence, not as a replacement for testing the actual assembly [3, 10, 11].

VI. SYSTEM-LEVEL METRICS AND EXPERIMENTAL PRACTICE

The reviewed literature supports paired reporting of thermal response and system cost. At minimum, a liquid-cooled module test should log multiple cell temperatures, coolant inlet and outlet temperatures, coolant flow, battery current/voltage, ambient temperature and the run duration. Pump and fan voltage/current or power should be measured; where

mist is used, its electrical demand and water consumption should be added. Relative humidity is necessary for interpreting evaporative performance [9–11].

For instrumented cell locations i , the reported maximum temperature is $T_{\max}(t) = \max[T_i(t)]$, and the measured spread is $\Delta T_{\text{cell}}(t) = \max[T_i(t)] - \min[T_i(t)]$. If coolant mass flow and its properties are known, an approximate heat pickup across the cooling section can be calculated as $\dot{Q}_{\text{cool}} = \dot{m} c_p (T_{\text{out}} - T_{\text{in}})$, using a stated sign convention. Auxiliary energy is obtained by integrating the measured pump, fan and mist-actuator power over the same interval. These calculations require sensors at the stated boundaries; transient heat storage in cells, tubes, coolant and surroundings prevents the coolant heat pickup alone from representing the complete battery heat generation.

A practical comparison uses matched cases: a safe reference condition, liquid cooling without mist, and

liquid cooling with radiator-side mist. The B-to-A difference estimates the contribution of liquid circulation; the C-to-B difference estimates the incremental mist contribution. Starting temperatures, electrical load, coolant setting, ambient temperature and test duration should be controlled or recorded. Repeated trials, calibration notes and uncertainty bounds should accompany conclusions, especially when temperature differences are small. Drive-cycle modeling has shown why coolant choice, ambient temperature and operating cycle can change system energy use [11].

VII. IMPLICATIONS FOR THE COPPER SERPENTINE-TUBE PROJECT

The source synopsis records that the conceptual/CAD design is complete and components have been procured, while assembly, commissioning and battery tests remain pending. The proposed configuration is indirect liquid cooling: heat passes from the battery module through a thermal interface to a copper serpentine-tube assembly, then to the coolant and radiator. A pump, reservoir and fan maintain circulation and heat rejection. The mist nozzle is planned for the radiator inlet air stream, not for direct battery impingement.

The literature suggests several verification steps before performance claims can be made. First, confirm whether the procured copper component is a tube, a plate with an embedded tube, or another geometry; ensure the CAD views, fittings and contact interface match the actual parts. Second, verify coolant compatibility, pressure ratings, flow direction, pump curve, radiator/fan ratings, cell chemistry and cell-manufacturer limits. Third, establish leak-free operation and electrical separation before powered battery trials. These checks define whether the proposed apparatus corresponds to the architecture assumed in the written plan.

A staged test program can then separate effects. A reference condition establishes the module's temperature rise under a safe approved load. A liquid-only case evaluates the serpentine loop. A matched liquid-plus-mist case evaluates any incremental radiator-air-side contribution. The measurements should include $T_{\max}$, ΔT_{cell} , coolant heat pickup, flow, accessory energy, ambient temperature and

humidity, and mist-water use. The analysis should report all valid repeats, not only the best run. Until such data exist, no cooling improvement, system efficiency gain or life-extension result can be attributed to this prototype.

VIII. RESEARCH GAPS AND FUTURE DIRECTIONS

The literature presents several research needs that are directly relevant to serpentine and mist-assisted BTMS. First, thermal and hydraulic objectives are often optimized separately. Future experiments should report both the temperature benefit and the pump power or pressure loss required to obtain it, so a design with greater heat transfer is not automatically treated as more efficient [5, 10, 11].

Second, channel-level findings do not always translate to a complete module or vehicle system. Research should document cell geometry, interface pressure/contact, flow maldistribution, radiator performance and pack-level sensor coverage. The serpentine microchannel experiment provides useful module-level evidence, but comparative studies still need harmonized loads, ambient conditions and boundaries before results can be directly ranked [3, 10].

Third, mist studies need a clear distinction between direct battery-surface spray, mist mixed into a cooling-air stream and radiator-side evaporative assistance. These architectures face different electrical, corrosion and water-management risks. Future reports should state nozzle droplet characteristics, mist loading, humidity, air velocity, evaporation fraction, carry-over and drainage. A cooling result achieved at a controlled humidity cannot be generalized to hot-humid operation without additional evidence [4, 9].

Fourth, system efficiency requires consistent accounting. Studies should measure pump, fan and mist-actuator power over matched intervals and identify whether vehicle HVAC or radiator loads are included. More real driving-cycle and repeatability work can help bridge the gap between small laboratory rigs and vehicle use [11, 12]. Finally, long-duration operation, leakage, fouling, corrosion, coolant ageing, control strategy and serviceability deserve evaluation alongside short-term thermal performance. These factors determine whether a cooling design can be maintained safely in practice [6–8, 17].

IX. CONCLUSION

This review finds that BTMS performance is a system property shaped by cell heat generation, interface quality, cooling-channel geometry, fluid flow, heat rejection, ambient conditions and auxiliary energy. Indirect liquid cooling is well suited to controlled heat transport, while serpentine configurations provide design flexibility at the cost of potential pressure loss. Mist cooling can add evaporative heat transfer, but it is sensitive to humidity and safe droplet management. Results from direct battery-mist experiments should not be transferred to a radiator-side mist arrangement without testing the changed boundary conditions.

For the proposed copper serpentine-tube prototype, the literature supports a controlled comparison of reference, liquid-only and liquid-plus-radiator-mist cases. Temperature uniformity, coolant response, accessory energy, ambient humidity and water use should be measured together. The synopsis reports design completion and component procurement, but assembly and testing are pending; therefore, no measured prototype benefit can yet be concluded. The main contribution expected from the project is a transparent, repeatable evaluation of its specific hardware and operating envelope.

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