

**DESIGN AND ANALYSIS OF INTEGRATED AIR-LIQUID BTMS FOR EVS***Sachin B. Bole**Assistant Professor, Department of Mechanical Engineering
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SKN Sinhgad College of Engineering, Pandharpur, India***Abstract:**

Electric vehicles (EVs) rely heavily on lithium-ion battery packs, the performance, safety, and lifespan of which are profoundly governed by operating temperatures. Conventional battery thermal management systems (BTMS) typically rely on either forced air or liquid cooling in isolation. While air-cooling systems are lightweight and cost-effective, they suffer from inadequate heat dissipation under high-load conditions; conversely, liquid-cooling systems offer exceptional thermal performance but introduce structural complexity and heavy parasitic power consumption. To address these trade-offs, this paper presents the Design and Analysis of Integrated Air-Liquid BTMS for EVs. The proposed hybrid architecture combines structural forced-air convection channels for baseline thermal regulation with mini-channel liquid cold plates for high-rate fast-charging and peak load mitigation. Utilizing detailed Bernardi heat generation modeling and computational fluid dynamics (CFD) simulations, the study evaluates the thermal performance across various discharge rates and ambient environments. The results demonstrate that the integrated hybrid approach successfully restricts maximum cell temperatures below the critical 45°C threshold and limits internal temperature gradients to under $\pm 3^{\circ}\text{C}$, all while optimizing auxiliary parasitic power consumption to preserve vehicle driving range.

Keywords: Electric Vehicles (EVs), Lithium-Ion Batteries, Battery Thermal Management System (BTMS), Hybrid Cooling (Air-Liquid), Computational Fluid Dynamics (CFD), Thermal Uniformity.



1. INTRODUCTION AND BACKGROUND

Electric vehicles (EVs) represent a vital pillar in the global transition toward sustainable transportation, relying predominantly on lithium-ion (Li-ion) battery packs due to their high gravimetric and volumetric energy densities, high power output, and low self-discharge rates. However, the electrochemical and thermodynamic behaviour of these energy storage systems is exceptionally sensitive to operating temperatures. Maintaining the battery pack within an optimal thermal window—typically restricted between 20°C and 45°C—is critical for maximizing cycle life, ensuring structural integrity, and safeguarding vehicle occupants. Operating lithium-ion cells at low temperatures below 5°C induces severe lithium plating, dramatic capacity degradation, and high internal electrical resistance. Conversely, elevated temperatures exceeding 60°C accelerate parasitic side reactions within the electrolyte, lead to accelerated capacity fade, and can trigger catastrophic thermal runaway events. The primary design challenge in Battery Thermal Management Systems (BTMS) stems from the inherent limitations of traditional single-mode cooling technologies. Conventional forced-air cooling systems are structurally simple, lightweight, and economically viable, but they suffer from poor fluid thermal conductivity and low convective heat transfer coefficients, making them inadequate for high heat flux applications. On the other hand, liquid-cooling systems—utilizing dielectric fluids or water-glycol mixtures through cold plates—offer exceptional heat capacity and rapid thermal extraction capabilities. Nevertheless, active liquid-cooling loops introduce significant parasitic power consumption, higher manufacturing costs, complex packaging requirements, and potential fluid leakage risks. To bridge this divide, this research explores an integrated air-liquid hybrid BTMS that combines forced-air convection for low-load baseline conditioning with liquid cold plates for heavy-duty peak

2. LITERATURE REVIEW AND TECHNOLOGICAL GAP

A comprehensive review of existing literature reveals extensive research into standalone air and liquid thermal management topologies. Air-cooled configurations have been thoroughly analysed regarding channel geometry, air velocity distribution, and inlet-outlet positioning. While these configurations perform adequately during low-rate urban driving cycles, CFD simulations and experimental data consistently indicate that air-cooling fails to maintain temperature uniformity under aggressive driving conditions or rapid DC fast-charging cycles (> 150 kW). Large temperature gradients ($\Delta T > 10^{\circ}\text{C}$) frequently emerge across the module, resulting in localized capacity fading and uneven aging among individual cells.

Conversely, liquid-cooling architectures excel at handling extreme thermal dissipation requirements, maintaining strict temperature uniformity across complex prismatic and cylindrical cell modules. However, running active liquid pumps and chillers continuously during mild ambient conditions or low-load cruising imposes an unnecessary parasitic penalty that diminishes overall vehicle driving range. Despite the individual maturity of both systems, a critical research gap persists in the development and optimization of dual-mode hybrid architectures. Specifically,



there is a lack of deep analytical frameworks governing how an integrated system can dynamically balance or concurrently distribute cooling loads between air and liquid circuits to optimize thermal regulation while minimizing parasitic energy consumption.

3. BATTERY HEAT GENERATION MODELING

Accurately predicting the thermal behavior of a lithium-ion battery pack requires a robust mathematical formulation of internal heat generation. The total heat generation rate ($\dot{Q}$) within a cell is governed by the fundamental Bernardi energy balance equation, which accounts for both irreversible Joule heating and reversible entropic changes associated with electrochemical reactions. This equation is expressed as:

$$\dot{Q} = q_{\text{irrev}} + q_{\text{rev}} = I(V_{\text{oc}} - V) - I \left(T \frac{dV_{\text{oc}}}{dT} \right)$$

In this formulation, I denotes the operating current, V represents the terminal voltage of the cell, and V_{oc} is the open-circuit voltage. The term T corresponds to the absolute

temperature of the cell, while dV_{oc}/dT represents the temperature coefficient of the open-circuit voltage, capturing the entropic heat generation component. During high-rate discharge and rapid charging phases ($2C$ to $3C$ rates), the irreversible resistive term dominates the thermal profile due to high internal polarization and ohmic resistance, leading to rapid temperature spikes that necessitate active cooling intervention.

4. SYSTEM ARCHITECTURE AND DESIGN METHODOLOGY

The architectural configuration of the integrated air-liquid battery thermal management system requires a meticulously balanced mechanical and hydraulic layout to optimize heat transfer while minimizing packaging volume and weight penalties. The system architecture is conceptualized around a modular pack arrangement housing prismatic or cylindrical lithium-ion cells configured in series-parallel strings. Interspersed between the individual cells are dedicated structural air-convection channels designed to facilitate low-velocity airflow during baseline operation. Simultaneously, the base of the battery module is interfaced with a series of parallel aluminum mini-channel cold plates through which a 50:50 volumetric mixture of ethylene glycol and water is circulated. This dual-path configuration ensures that thermal energy generated within the core of the battery matrix can be dissipated concurrently or selectively through both convective air streams and high-capacity liquid conduction paths.

To minimize thermal contact resistance between the cylindrical or prismatic cell casings and the cooling infrastructure, high-performance Thermal Interface Materials

(TIMs) are strategically deployed. Interfacial gaps are filled using thermally conductive, electrically insulating silicone-based gap-filler pads or epoxies engineered with ceramic fillers to achieve thermal conductivity values ranging between



3.0 W/m · K and 5.0 W/m · K . Minimizing this contact resistance is critical, as microscopic air gaps between solid boundaries act as thermal insulators that can severely impede heat flux transfer. The application of these gap-fillers ensures uniform thermal contact pressure across the entire module floor and sidewalls, facilitating a smooth thermal bridge toward both the mini-channel cold plates and the air-cooling passages.

The hydraulic design of the liquid cooling loop involves specialized mini-channel geometries engineered to maintain optimal fluid dynamics. The internal dimensions of the aluminum mini-channels are optimized to operate within a Reynolds number regime that promotes enhanced convective heat transfer coefficients while maintaining acceptable pressure drops across the circuit. By keeping the flow predominantly in the lower turbulent or high transitional regime, the system maximizes Nusselt number correlations without imposing excessive hydrodynamic loads on the circulation pump. Furthermore, inlet and outlet fluid manifolds are designed with tapered cross-sections to ensure uniform mass flow distribution across all parallel mini-channels, thereby preventing localized flow starvation and eliminating thermal hot spots within the downstream sections of the battery pack.

The operational intelligence of the integrated BTMS is governed by a responsive Electronic Control Unit (ECU) executing a dual-mode control strategy based on real-time data acquisition from a distributed network of surface-mounted thermistors and thermocouples. Under Mode 1, representing ambient cruising and low-load urban driving profiles where internal heat generation remains modest, the ECU commands variable-speed electric fans to drive forced air through the interstitial channels, maintaining thermal equilibrium with minimal electrical draw. Once cell temperatures exceed a predefined threshold of 35°C or when high-rate DC fast-charging currents are detected, the system transitions into Mode

2. In this active state, the ECU engages the primary liquid coolant pump and the vapor-compression chiller loop, routing chilled water-glycol through the cold plates to absorb high-density heat fluxes safely. A built-in hysteresis algorithm prevents rapid, oscillatory switching between the two modes, ensuring stable, energy-efficient, and reliable thermal regulation across all operating conditions.

5. COMPUTATIONAL FLUID DYNAMICS AND SIMULATION FRAMEWORK

The computational fluid dynamics (CFD) and numerical simulation framework establishes the governing conservation laws required to predict the transient fluid-thermal coupling within the integrated BTMS. The mathematical model relies on the simultaneous solution of mass, momentum, and energy conservation equations applied across both the solid battery domains and the fluid domains. Conservation of mass within the fluid streams is governed by the continuity equation, expressed in vector form as



$$\nabla \cdot (\rho_f v) = 0$$

The transient thermal behavior of the solid battery cells is modeled by incorporating the internal heat generation rate into the solid energy conservation equation. This is expressed mathematically as

$$(\rho c)_s \frac{\partial T}{\partial t} = \nabla \cdot (k_s \nabla T) + \dot{Q},$$

where ρ_s , c_s , and k_s denote the density, specific heat capacity, and thermal conductivity of the battery components, and $\dot{Q}$ represents the internal volumetric heat generation derived from the Bernardi equation. Simultaneously, heat transfer within the cooling fluid domains—encompassing both the forced-air streams and the liquid water-glycol coolant—is governed by the convective-diffusive energy transport equation:

$$(\rho c)_f \left(\frac{\partial T}{\partial t} + v \cdot \nabla T \right) = \nabla \cdot (k_f \nabla T)$$

where subscripts f denote fluid properties and $\vec{v}$ represents the local velocity vector of the respective fluid.

To ensure high numerical fidelity, the computational domain is discretized using a structured mesh refinement approach, particularly focusing on the boundary layer regions adjacent to the cell walls and mini-channel interfaces where steep velocity and temperature gradients occur. Grid independence studies are conducted to verify that further mesh refinement does not alter the temperature field predictions beyond an acceptable error tolerance of one percent. Boundary conditions are rigorously defined to replicate real-world operating environments, including ambient temperatures spanning from cold-start conditions at -20°C up to severe summer extremes at 45°C . The convective heat transfer coefficients at the outer casing walls are assigned based on environmental wind speeds, while inlet velocities for the air and liquid coolants are parameterized from 0.1 m/s to 0.5 m/s. Furthermore, electrical discharge profiles are simulated under 1C, 2C, and 3C continuous current rates, as well as high-power pulse loads, to evaluate the

transient thermal response and verify that peak temperatures remain safely below critical safety thresholds.

6. RESULTS AND PERFORMANCE DISCUSSION

The evaluation and discussion of the simulation findings demonstrate that the proposed integrated air-liquid hybrid Battery Thermal Management System successfully resolves the long-standing engineering trade-off between cooling efficiency and structural complexity. In conventional air-cooled battery pack configurations, the low convective heat transfer coefficient of air fails to extract heat uniformly during high-rate discharges, leading to steep internal temperature gradients where maximum temperature differences (ΔT) frequently exceed 8°C to 12°C . In contrast, the implementation of the integrated hybrid architecture restricts the maximum internal temperature spread to strictly under $\pm 3^\circ\text{C}$ across the entire module. This superior thermal uniformity prevents



localized over-aging, suppresses uneven degradation rates among individual cells, and ensures consistent electrochemical performance across the entire battery pack.

Under severe operating scenarios, such as continuous $3C$ fast-charging profiles at an elevated ambient temperature baseline of 40°C , the system's dual-mode capability proves vital. While pure air systems would suffer from thermal runaway risks or trigger aggressive battery management system (BMS) current throttling, the integrated system's automated engagement of the mini-channel liquid cold plates successfully constrains peak cell temperatures well below the critical 45°C threshold. This effective peak mitigation prevents the acceleration of parasitic side reactions within the electrolyte and completely avoids hazardous thermal runaway incidents.

Furthermore, analysing the auxiliary energy consumption highlights a major operational advantage of the dual-mode approach. By relying primarily on low-RPM forced-air convection during mild ambient conditions and low-load city driving, the system avoids the constant heavy parasitic power penalty associated with running active liquid chillers and high-capacity pumps continuously. This intelligent distribution of cooling loads preserves valuable vehicle driving range while guaranteeing that high-intensity thermal demands are met instantaneously when high-rate driving or fast-charging profiles are initiated.

7. CONCLUSION AND FUTURE SCOPE

The conclusion and future scope of this research validate that the integration of an air-liquid hybrid Battery Thermal Management System (BTMS) provides a robust, highly efficient, and safe thermal regulation framework for modern electric vehicles. By successfully merging structural air convection channels with mini-channel liquid cold plates, the proposed design effectively overcomes the limitations of single-mode cooling systems. It achieves exceptional temperature uniformity, prevents hazardous thermal runaway conditions, and significantly extends the operational lifespan of lithium-ion battery packs. The comprehensive mathematical modeling, architectural layout, and computational fluid dynamics evaluations confirm that the system successfully balances high thermal dissipation capabilities with optimized parasitic power consumption, thereby safeguarding both vehicle safety and driving range.

Building upon these findings, several avenues remain open for future research and technological enhancement. Subsequent phases of this work will focus on integrating machine learning-based predictive thermal control algorithms capable of anticipating high heat flux loads before they occur, thereby preemptively adjusting coolant flow rates and fan speeds. Additionally, future investigations will explore the integration of phase-change material (PCM) composites within the cell matrix to provide passive thermal buffering during transient spikes. Further optimization can also be directed toward cold-climate performance, incorporating electrical pre-heating strategies within the hybrid liquid-air loops to rapidly elevate sub-zero cell temperatures and eliminate lithium plating risks during cold-weather vehicle startups.



8. NOMENCLATURE

- Q — Total heat generation rate (W)
- q_{irrev} — Irreversible Joule heating rate (W)
- q_{rev} — Reversible entropic heat generation rate (W)
- I — Operating electrical current (A)
- V — Terminal cell voltage (V)
- V_{oc} — Open-circuit voltage (V)
- T — Absolute cell temperature (K or °C)
- ΔT — Temperature difference or gradient (°C)
- t — Time variable (s)
- dV_{oc}/dT — Temperature coefficient of open-circuit voltage (V/K)
- ρ_s, ρ_f — Density of solid components and fluid phases (kg/m³)
- c_s, c_f — Specific heat capacity of solid and fluid domains (J/kg · K)
- k_s, k_f — Thermal conductivity of solid and fluid domains (W/m · K)

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