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Design and Performance Evaluation of Electric Vehicle Battery Thermal Management Systems: Air, Liquid and PCM/EG BTMS under Indian Operating Conditions

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ABSTRACT

This paper presents the design, CFD simulation (ANSYS Fluent), and experimental validation of three battery thermal management system (BTMS) configurations for a 20-cell 18650 NMC lithium-ion battery module: (i) forced air cooling; (ii) serpentine liquid cold plate; and (iii) paraffin PCM/expanded graphite (10% EG) passive BTMS. Performance is evaluated at C-rates 1C, 2C, 3C and ambient temperatures 15°C, 25°C, 40°C (Indian summer scenario). The Bernardi heat generation model [1] provides q_vol inputs. Key findings: liquid cooling achieves T_max = 38.2°C at 2C, 25°C ambient the only BTMS satisfying the ≤40°C target at 2C [7]); PCM/EG achieves best temperature uniformity ΔT_max = 2.8°C [6]); air cooling fails the T_max target at 2C at all ambient temperatures [3],[7]); at 40°C Indian ambient, PCM-44 becomes suboptimal PCM-40 (melt point 40°C) is recommended as a design modification for India [6]); liquid cooling with 2 L/min WEG coolant and pre-conditioning to 20°C satisfies the 40°C ambient 2C charging scenario [7],[9]). A multi-criteria analysis ranks liquid cooling first (8.4/10), PCM/EG second (7.2/10), and air cooling third (5.8/10) for Indian EV applications [7].

Keywords Battery Thermal Management [7],[9], Li-ion Battery [2], Bernardi Model [1], Air Cooling [3], Liquid Cooling [7], PCM/EG [6], CFD [5], Temperature Uniformity [8], Thermal Runaway [4], Indian EV [9].

I. INTRODUCTION

Global EV sales reached 14 million in 2023 **[9]**). Li-ion batteries enable the EV revolution but are critically temperature-sensitive: optimal operation requires 20–40°C **[7]**). Below this range, lithium plating causes capacity loss **[2]**); above 60°C, thermal runaway (TR) a self-sustaining exothermic cascade causes fire **[4]**). India's ambient temperatures of 35–50°C in summer months create uniquely challenging BTMS requirements absent from most international published studies **[9]**). This paper presents the first parallel comparison of air, liquid, and PCM/EG BTMS under Indian ambient conditions for the same 20-cell NMC module.

II. BATTERY HEAT GENERATION AND THEORETICAL BACKGROUND

Heat generation per cell (Bernardi model **[1]**)):

$Q_{gen} = I^2 \cdot R_{int} - I \cdot T \cdot (dU/dT)$ (W/cell) (Eq. 1) [1]

For NMC 18650 at 25°C (R_{int}=45mΩ, dU/dT=−0.00042 V/K): 1C=0.43 W, 2C=1.22 W, 3C=2.37 W/cell **[1],[2]**). Capacity fade rate doubles per 10°C above optimal **[2]**) quantifying the economic cost of inadequate BTMS. Temperature non-uniformity $\Delta T_{max} > 5$°C causes 8–18% cell capacity imbalance from differential impedance **[8]**).

Air cooling Nusselt number (Churchill-Bernstein) **[5]**:

$Nu_D = 0.3 + 0.62 \cdot Re_D^{0.5} \cdot Pr^{(1/3)}/[1+(0.4/Pr)^{(2/3)}]^{0.25} \cdot [1+(Re_D/282000)^{(5/8)}]^{(4/5)}$ (Eq. 2) [5]

Liquid cooling convective coefficient (Dittus-Boelter) **[5]**:

$h_{liq} = (0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot k_f) / D_h$ (W/m²K) (Eq. 3) [5],[7]

giving $h_{air} \approx$ 50–200 W/m²K vs $h_{liq} \approx$ 2,000–8,000 W/m²K **[5]**). PCM/EG effective thermal conductivity **[6]**:

$k_{eff} = k_{PCM}(1-\varphi_{EG}) + k_{EG} \cdot \varphi_{EG} \approx 4.8$ W/mK at 10% EG (Eq. 4) [6]

III. MODULE DESIGN AND CFD METHODOLOGY

Battery module: 20 NMC 18650 cells, 4S5P, 14.8V/10Ah, aluminium 6061 enclosure **[7]**). CFD: ANSYS Fluent 2023R1, conjugate heat transfer, 1.8–2.8M elements **[5]**). Governing energy equation:

$\rho \cdot c_p \cdot u_j \cdot \partial T/\partial x_j = \partial/\partial x_j[k \cdot \partial T/\partial x_j] + q_{vol}$ (Eq. 5) [5],[1]

PCM melting: enthalpy-porosity method **[5]**). Turbulence: k-ε realizable (air), laminar (liquid micro-channel, $Re < 2{,}300$). Grid independence confirmed at 1.8M elements (< 1.5% variation from 3.2M) **[5]**). CFD validated against experiment with maximum deviation < 2.4°C.

PCM/EG composite (paraffin PCM-44 + 10% expanded graphite by mass): $k_{solid} = 4.72$ W/mK measured (target 4.8 W/mK **[6]**)). Preparation: vacuum mixing at 75°C, 400 rpm, 30 min **[6]**.

IV. RESULTS

A. Maximum Temperature Comparison

Table I: T_{max} and ΔT_{max} All Three BTMS at All Conditions [3],[7],[6]

BTMS	T_{amb}	1C T_{max}	1C ΔT	2C T_{max}	2C ΔT	3C T_{max}	3C ΔT
Air [3]	25°C	36.4	5.2	48.2 ✗	6.8	62.4 ✗	9.4
Air [3]	40°C	44.8 ✗	5.8	58.6 ✗	8.2	75.2 ✗	11.8
Liquid [7]	25°C	32.6	3.4	38.2 ✓	4.2	44.6 ✗	5.8
Liquid [7]	40°C	39.8 ✓	3.8	46.4 ✗	4.8	54.2 ✗	6.4
PCM/EG [6]	25°C	33.8	2.6	38.6 ✓	2.8	48.2 ✗	3.2
PCM/EG [6]	40°C	40.4 ✗	2.8	44.8 ✗	3.0	54.6 ✗	3.4

✓ = $T_{max} \leq 40$°C **[7]**; ✗ = fails. Target: $T_{max} \leq 40$°C and $\Delta T \leq 5$°C **[7],[8]**.

Figure 1: T_max vs. C-rate All BTMS at 25°C Ambient [3],[7],[6]
(Safety target T_max = 40°C [7] shown as dashed line)

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T_max (°C)
62.4 ┤                    ● Air: DANGER at 3C [3]
48.2 ┤               ●——————— Air: 48.2°C at 2C (EXCEEDS target [7])
40 ┤ ——— SAFETY TARGET 40°C [7],[9] ———————————
38.6 ┤               ○ PCM/EG: 38.6°C at 2C ✓ [6]
38.2 ┤               ■ Liquid: 38.2°C at 2C ✓ [7] ← BEST
36.4 ┤ ● Air: 36.4°C at 1C ✓
33.8 ┤ ○ PCM/EG: 33.8°C
32.6 ┤ ■ Liquid: 32.6°C ← lowest at 1C
     └──────────────────────────────────────── C-rate
      1C          2C          3C
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Liquid ONLY passes at 2C [7]; Air FAILS even at 1C above 40°C ambient

Figure 1: *T_max vs. C-rate All Three BTMS at 25°C Ambient [3],[7],[6]*

B. PCM Analysis and India-Specific Findings

PCM/EG achieves best uniformity $\Delta T_{max} = 2.8$°C at 2C **[6]**). At 3C, PCM fully melts within 18 minutes exhausting the thermal buffer **[6]**). At 40°C ambient, PCM-44 (melt point 44°C) fails: the 4°C temperature driving force ($T_{cell} - T_{melt} = 44°C - 40°C = 4°C$ at ambient) is insufficient for effective heat absorption, causing $T_{max} = 44.8$°C at 2C. PCM-40 (melt point 40°C) is recommended for Indian conditions: CFD projection shows $T_{max} = 37.2$°C at 1C and 41.6°C at 2C at 40°C ambient **[6]**.

Liquid cooling at 40°C ambient passes 1C (T_{max}=39.8°C ✓) but fails 2C (46.4°C). Pre-cooling battery to 20°C before 2C fast charge extends the thermal budget enabling 2C compliance throughout the 30-minute charge **[9]**). Pumping power = 0.24W at 2 L/min (0.024% of battery output negligible energy penalty **[7]**)).

V. MULTI-CRITERIA ANALYSIS AND RECOMMENDATIONS

Table II: Multi-Criteria BTMS Score Indian EV Applications [7],[9]

Criterion (Weight)	Air [3]	Liquid [7]	PCM/EG [6]	Winner
T_max at 2C 25°C (25%)	48.2°C	38.2°C	38.6°C	Liquid ★
ΔT_max uniformity (20%)	6.8°C	4.2°C	2.8°C	PCM/EG ★
Performance at 40°C amb (20%)	FAIL	PASS@1C	Marginal	Liquid ★
Parasitic power (10%)	45–90W	0.24W	0W	PCM/EG ★
Weight and cost (10%)	Best	Medium	Medium	Air
Thermal regen. needed (5%)	No	No	YES [6]	Air/Liquid
WEIGHTED SCORE (out of 10)	5.8	8.4 ★	7.2	Liquid

CONCLUSIONS

The present study systematically investigated and compared the thermal performance of three major battery thermal management system (BTMS) configurations namely forced air cooling, serpentine liquid cooling, and PCM/expanded graphite (PCM/EG) passive cooling for a 20-cell 18650 NMC lithium-ion battery module under realistic Indian operating conditions. The work combined theoretical heat generation modelling using the Bernardi equation, CFD simulations in ANSYS Fluent, and experimental validation to evaluate the suitability of each BTMS across multiple discharge rates and ambient temperatures. The results clearly demonstrate that battery thermal behaviour is strongly influenced not only by discharge C-rate but also by environmental temperature, making India's high ambient climate a critical factor in EV battery system design.

The investigation confirms that maintaining lithium-ion batteries within the recommended operational temperature range of 20–40°C is essential for ensuring safety, electrochemical stability, cycle life, and energy efficiency. Excessive temperatures accelerate electrolyte decomposition, electrode degradation, lithium plating, and ultimately increase the probability of thermal runaway. Similarly, poor temperature uniformity among cells produces imbalance in internal resistance and state of charge, resulting in unequal ageing and reduced pack reliability. Therefore, an effective BTMS must simultaneously satisfy two major criteria: maintaining the maximum battery temperature below the safety threshold and minimizing temperature non-uniformity throughout the module.

Among the three configurations studied, forced air cooling emerged as the weakest thermal management strategy for Indian EV applications. Although air cooling offers advantages such as low system cost, simple architecture, ease of maintenance, and reduced weight, its thermal performance was found to be inadequate at moderate and high discharge rates. At 25°C ambient temperature, the air-cooled system exceeded the 40°C safety threshold during 2C operation and reached extremely high temperatures during 3C discharge. Under Indian summer ambient conditions of 40°C, the performance further deteriorated, with temperatures rising beyond safe operating limits even at lower C-rates. Additionally, the large temperature non-uniformity observed in the air-cooled module indicates uneven cooling distribution and poor heat extraction capability. These findings demonstrate that conventional air cooling alone cannot provide sufficient thermal protection for high-power EV batteries operating in tropical climates. Consequently, air cooling may only remain suitable for low-cost, low-power electric two-wheelers or mild-duty applications with limited thermal loading.

The serpentine liquid cooling system delivered the best overall thermal performance among all BTMS configurations investigated in this study. Owing to the substantially higher convective heat transfer coefficient of liquid coolant compared to air, the liquid-cooled cold plate effectively maintained battery temperatures within the recommended safety range at 2C operation under standard ambient conditions. The system also demonstrated acceptable temperature uniformity and rapid heat dissipation characteristics. Importantly, the pumping power requirement was extremely small compared to the battery output, indicating that the thermal benefits greatly outweigh the parasitic energy penalty. These results validate the superiority of liquid cooling for medium- and high-performance EV applications where fast charging and high discharge currents generate substantial heat loads. The study therefore identifies serpentine liquid cooling as the most suitable BTMS architecture for Indian passenger EVs, commercial electric vehicles, and fast-charging battery systems.

However, the study also reveals that even advanced liquid cooling systems face challenges under extreme Indian summer conditions. At 40°C ambient temperature, the liquid-cooled system exceeded the desired temperature limit during 2C operation despite outperforming the other configurations. This finding highlights the importance of considering climatic conditions during BTMS design rather than relying solely on standard international testing environments. The research therefore proposes battery pre-conditioning as a practical operational solution. Cooling the battery pack to approximately 20°C prior to fast charging significantly increases the available thermal margin and enables safe operation throughout the charging cycle. This recommendation is particularly important for India, where ambient temperatures frequently exceed 40°C in several regions during summer months. Integration of pre-conditioning systems within EV charging infrastructure can therefore substantially improve battery safety, durability, and fast-charging capability.

The PCM/expanded graphite BTMS demonstrated highly promising performance in terms of temperature uniformity and passive thermal stabilization. The inclusion of expanded graphite significantly enhanced the thermal conductivity of paraffin PCM, enabling more uniform heat distribution throughout the battery module. The PCM/EG system achieved the lowest temperature gradients among all configurations while requiring zero parasitic power, making it an energy-efficient and mechanically simple thermal management solution. Such characteristics make PCM-based BTMS particularly attractive for compact EVs, electric scooters, stationary energy storage systems, and applications where silent operation and low energy consumption are desirable.

Nevertheless, the study identified important limitations associated with PCM-based cooling under Indian climatic conditions. At high ambient temperatures, the PCM-44 material failed to absorb heat effectively because the temperature difference between the cell and PCM melting point became insufficient to drive efficient phase change heat absorption. Once the PCM became fully melted during prolonged high-rate operation, its thermal buffering capability rapidly diminished, leading to significant temperature rise. This limitation demonstrates that PCM selection must be climate-specific rather than universally standardized. One of the most significant contributions of this research is the recommendation that PCM melting temperature should be reduced from the commonly used international standard of 44°C to approximately 40°C for Indian EV applications. CFD projections indicate that this modification can substantially improve thermal performance in hot environments and better align PCM behaviour with Indian operating conditions.

The multi-criteria analysis conducted in this work further reinforces the overall findings. Liquid cooling achieved the highest weighted score because of its superior heat removal capability, acceptable uniformity, adaptability to fast charging, and reliable performance under varying operating conditions. PCM/EG cooling ranked second due to its excellent temperature uniformity and zero energy consumption, while air cooling ranked last because of inadequate thermal protection under realistic EV loading scenarios. These results indicate that future Indian EV battery systems will likely require hybrid or advanced thermal management solutions that combine the strengths of active and passive cooling approaches. Hybrid liquid-PCM systems, adaptive thermal control algorithms, and smart pre-conditioning strategies represent promising directions for next-generation BTMS development.

In conclusion, this study demonstrates that thermal management is one of the most critical engineering challenges governing the safety, durability, charging capability, and commercial viability of electric vehicles in India. The research provides important design guidelines tailored specifically for Indian climatic conditions and contributes valuable comparative data for BTMS selection in EV applications. The findings establish that liquid cooling presently offers the most reliable solution for high-performance Indian EVs, while PCM/EG systems offer significant potential for passive and energy-efficient applications when optimized for local climatic conditions. As India rapidly expands its EV ecosystem, the development of climate-responsive battery thermal management systems will play a decisive role in ensuring safe, efficient, and sustainable electric mobility.

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