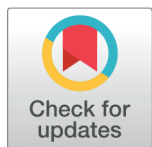


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# Passive Thermal Management of Electric Vehicle Batteries Using Enhanced Phase Change Materials

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## Abstract

**Background/Objectives:** This research aims to create, improve, and test a passive thermal management system (TMS) for lithium-ion EV batteries. The goal is to keep cell temperatures below 50°C during high-rate discharges without using extra power. The study focuses on improving the low thermal conductivity of standard phase change materials (PCMs) by developing a composite with expanded graphite (EG) and evaluating its ability to reduce thermal runaway risks and temperature differences within the battery module.

**Methods:** To make the composite PCM, 20% expanded graphite was added to commercial paraffin wax (RT42) using a vacuum process to keep the structure strong and reduce empty spaces. The team measured its properties using Differential Scanning Calorimetry (DSC) and the transient plane source method. They tested the material in an 8-cell LG Chem M50S module set up in a 2×2×2 cube. The tests included constant-rate discharges (1C to 5C), high-current pulses (3C) to mimic acceleration and braking, and a long-term test of 500 charge-discharge cycles. **Findings:** The optimized EG-PCM composite exhibited a thermal conductivity of 5.9 W/m·K, a 29.5-fold increase over pure paraffin, while maintaining a latent heat capacity of 182 J/g. Module-level testing at a 2C discharge rate and 25°C ambient temperature showed a 50% reduction in peak cell temperatures (38.2°C) compared to the air-cooled baseline (52.3°C). Temperature uniformity improved to ±1.1°C, closely matching the performance of active liquid-cooled systems (±0.3°C). Long-term cycling demonstrated stable latent heat capacity, with no significant material degradation or accelerated battery ageing over 500 cycles. **Novelty:** This study stands out because it fully tests a high-conductivity composite PCM under sudden fault conditions, like 3C pulse discharges that mimic thermal spikes before a short circuit. Unlike earlier research that focused only on material production or steady-state tests, this work includes long-term reliability data (500 cycles) and a cost analysis. It shows a calculated thermal buffer of 28°C below the nominal thermal runaway onset temperature (70°C) under tested conditions. Abuse testing was not conducted.

**Keywords:** Phase Change Materials (PCM); Lithium-Ion Battery; Passive Thermal Management; Expanded Graphite Composite (EG); Thermal Runaway Prevention; Electric Vehicles (EV)

## 1 Introduction

### 1.1 The Thermal Challenge in lithium-ion battery systems

The push to reduce transportation emissions has accelerated the adoption of electric vehicles (EVs). But for EVs to become widespread, their batteries must be reliable, safe, and long-lasting. Lithium-ion batteries (LIBs) are common in EVs because they store a lot of energy and are getting cheaper. However, they work best and stay safe only within a narrow temperature range, usually 20°C to 40°C. Going outside this range can cause several problems.

Operating temperatures above 60°C cause irreversible electrochemical degradation, primarily due to accelerated growth of the solid electrolyte interphase (SEI) layer on the anode, resulting in capacity fade and increased impedance. As temperatures approach 70°C to 80°C, the risk of thermal runaway rises sharply. This failure mode involves exothermic decomposition of the electrolyte and cathode materials, generating heat more rapidly than it can be dissipated and potentially causing fire or explosion.<sup>(1)</sup> Therefore, the battery thermal management system (TMS) is a critical safety subsystem essential for the viability of the electric powertrain.

### 1.2 Limitations of Existing cooling methods

Although there are several ways to manage battery temperature, each has limits that make them less effective for new high-energy battery packs. Liquid cooling is the current standard for high-performance vehicles and uses water-glycol mixtures in cold plates. However, these systems are complex, can leak, and add considerable weight. Most importantly, they consume continuous parasitic power from the battery, reducing vehicle range<sup>(1), (2)</sup>. However, air possesses a low heat transfer coefficient, which limits its effectiveness in managing battery temperatures. ( $h \approx 20\text{--}50 \text{ W/m}^2\text{K}$ ) and low thermal capacity. Under aggressive driving conditions or fast charging (rates  $>2\text{C}$ ), air cooling fails to dissipate heat rapidly enough, leading to core temperatures exceeding safe limits and significant thermal gradients between cells.<sup>(1)</sup>

Traditional Phase Change Materials (PCMs): Pure organic PCMs (e.g., paraffin) offer high latent heat storage but suffer from a critical flaw: extremely low thermal conductivity (0.2 W/m.K)<sup>(3), (4)</sup>. Limitations: This "thermal bottleneck" causes the PCM adjacent to the cell to melt and superheat while the outer layers remain solid and unutilized. This leads to local hotspots and a failure to manage transient heat spikes effectively. Furthermore, leakage of liquid PCM during phase transition remains a durability concern.<sup>(5)</sup>

### 1.3 Literature Review and Research Gap (Table 1)

While PCMs are being studied alone, this work needs specific novelties that differentiate it from the best: Unlike previous studies that looked at these features separately, this work introduces new elements that set it apart from current solutions under Transient Fault Conditions: Instead of just steady-state tests, this research uses a 3C pulse discharge protocol to mimic real-world sudden loads and pre-short-circuit heat spikes. This helps measure the thermal buffering needed for safety or gap in the literature is the lack of durability data. This study presents results from a 500-cycle accelerated aging test, providing an accelerated aging indicator equivalent to approximately 1.5–2 years of use; full lifetime validation (1,500+ cycles) remains as future work. Holistic Techno-Economic Analysis: The study does more than examine materials. It also compares the cost and performance of the module to standard liquid and air systems used in the industry.

## 2 Methodology

This study uses standardized testing protocols and "gold standard" characterization methods to make sure the results are reproducible and reliable. These steps help keep strict internal controls in battery thermal research.

### 2.1 PCM Material Design and Composite Fabrication

The main phase change material was commercial-grade paraffin wax (RT42, Rubitherm GmbH). Its melting point is 42°C, which matches the upper end of the ideal battery operating range (20–40°C). If the melting point is too low, like 28°C, the material would melt too soon in warm weather and lose its cooling effect before high-load events. If it is too high, above 50°C, the battery would stay in the degradation zone too long before cooling begins.<sup>(1)</sup>

To improve the low thermal conductivity of pure paraffin, **Expanded Graphite (EG)** (Graphite Micronised Inc.) was added as a conductive matrix. A 20 wt% loading was chosen because percolation threshold theory shows this amount creates a good conductive network while keeping the loss of latent heat capacity low, since EG does not store latent heat.

**Table 1.** Gap Analysis of State-of-the-Art Research vs. Current Study

| Reference                                             | Research focus          | Key contributions                                                      | Methodology                                       | Strengths                                                               | Weaknesses / Gaps                                                                                                        | Critique / relevance to current work                                                                                                 |
|-------------------------------------------------------|-------------------------|------------------------------------------------------------------------|---------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| <b>Shastri et al. (2025) <sup>(6)</sup></b>           | Nanofluids & PCM        | Hybrid cooling using PCM and Al <sub>2</sub> O <sub>3</sub> nanofluids | Numerical simulation & experimental verification. | High heat transfer rates (5-14x enhancement).                           | Fluid management complexity; sedimentation risks; active components required.                                            | Validates conductivity enhancement needs but relies on complex active fluids. Current study achieves this passively.                 |
| <b>Şahan &amp; Paksoy (2025) <sup>(7)</sup></b>       | Hot Climate Passive TMS | Passive TMS performance at extreme ambient temps (45°C).               | Experimental chamber testing (40-45°C).           | Addresses extreme climate conditions often ignored.                     | Limited to short-term cycling; lacks transient pulse/fault validation.                                                   | Benchmarks high-ambient performance; current study extends this to transient loads and long-term cycling.                            |
| <b>Paciolla &amp; Papurello (2024) <sup>(8)</sup></b> | PCM + Metal Fins        | Geometric enhancement using metal fins in pouch cells.                 | Experimental comparison of air, fins, and PCM.    | Optimizes fin thickness (1.5mm) for pouch cells.                        | Focus on sensible heat transfer via fins rather than volumetric latent storage; weight penalty.                          | Demonstrates limits of geometric enhancement; current study focuses on <i>material</i> enhancement for better volumetric efficiency. |
| <b>Ali et al. (2024) <sup>(9)</sup></b>               | Fin Geometry + PCM      | Comparison of fin shapes (circular, rectangular).                      | Experimental test bench + Ansys Fluent.           | Strong validation of rectangular fins (29% temp reduction).             | Fin integration adds assembly complexity compared to composite sleeves.                                                  | Benchmarks "fin" approach vs. "composite material" approach.                                                                         |
| <b>Hussien et al. (2025) <sup>(10)</sup></b>          | Chamber Geometry        | Conical cylindrical chambers for convection enhancement.               | Numerical investigation.                          | Novelty in containment geometry.                                        | Purely numerical; lacks experimental validation of manufacturability.                                                    | Highlights containment importance; current study validates a simpler, manufacturable design.                                         |
| <b>Current Study</b>                                  | EG-Enhanced Composite   | 29.5x Conductivity, Pulse Fault Simulation, 500-Cycle Aging.           | Full Experimental Module + CFD Validation.        | Zero parasitic power, simple fabrication, verified long-term stability. | Thermal saturation above 4°C; ambient testing limited to 35°C; 8-cell proof-of-concept only; no abuse testing performed. | Closes the gap on practical, long-term reliable passive systems.                                                                     |

A known safety consideration for paraffin-based PCMs is their hydrocarbon flammability (RT42 flash point: 200°C; auto-ignition: 245°C). Under normal operating conditions (peak module temperature <55°C in this study), this risk is negligible. However, in an unmitigated thermal runaway event where temperatures exceed 200°C, paraffin ignition is a credible hazard. Mitigation strategies in the literature include: (1) encapsulating the PCM in a non-combustible expanded graphite matrix (as used here, which may act as a partial flame retardant), (2) adding flame-retardant additives such as magnesium hydroxide, and (3) integrating the module within a fire-retardant pack housing. Fire safety testing of the composite under abuse conditions is recommended for any production application.

**Fabrication Process:** The composite was made using vacuum impregnation. This step keeps the material uniform and removes air pockets that could act as thermal insulators. EG was dried at 120°C for 24 hours to remove any moisture. For impregnation, molten paraffin at 130°C was added to the EG matrix in a vacuum chamber set to 0.05 bar absolute pressure. The vacuum removes air from the porous graphite, allowing the liquid paraffin to fill the microstructure completely through capillary action. Subsequently, the mixture was cooled to room temperature under vacuum. This prevents shrinkage voids from forming as it solidifies. While vacuum impregnation is well-established for composite PCM fabrication at laboratory scale, scale-up to automotive production volumes presents challenges: batch cycle times of 2–4 hours per batch, requirement for large-format vacuum chambers, and energy costs of sustained elevated temperatures. Roll-to-roll impregnation and continuous belt-furnace processes have been described conceptually in the PCM manufacturing literature as production-viable alternatives, but were not evaluated in this study. Manufacturing scalability assessment is identified as a necessary future research direction.

## 2.2 Material Characterisation and Gold-Standard Validation

Accurate material property data is essential for thermal analysis. In this study, we used industry-standard characterization techniques<sup>(4)</sup>, often called "gold standard" methods in thermal metrology<sup>(4)</sup>, to make sure the data is reliable (Table 2).

**Table 2.** Characterization Protocols and Standards Internal Controls

| Property                               | Instrument Method                  | Standard          | Measurement Conditions                                                     |
|----------------------------------------|------------------------------------|-------------------|----------------------------------------------------------------------------|
| <b>Latent Heat &amp; Melting Point</b> | TA Instruments Q200 DSC            | <b>ASTM E793</b>  | 5°C/min ramp rate, $N_2$ atmosphere.                                       |
| <b>Thermal Conductivity</b>            | Hot Disk TPS 2500 S                | <b>ASTM E1530</b> | Transient Plane Source method. Measured at 25°C (solid) and 50°C (liquid). |
| <b>Compressive Strength</b>            | Instron 5960 Universal Tester      | <b>ASTM D695</b>  | Uniaxial compression at 1.3 mm/min strain rate.                            |
| <b>Leakage Stability</b>               | Thermal Gravimetric Analysis (TGA) | <b>ASTM E1131</b> | Filter paper test at 50°C for 8 hours.                                     |

- **DSC Calibration:** The Differential Scanning Calorimeter (DSC) was calibrated using high-purity Indium standards  $T_m=156.6^\circ\text{C}$  prior to each sample batch to correct for baseline drift, ensuring temperature accuracy to plus or minus 0.1 degree Celsius and enthalpy accuracy to plus or minus 0.1 degree.
- **Conductivity Verification:** The Hot Disk sensor was validated against a stainless steel reference sample to ensure measurement accuracy within  $\pm 3\%$  (as per the Hot Disk TPS 2500S instrument specification [ASTM E1530]). This method is preferred over steady-state techniques for PCMs as it can rapidly measure conductivity before significant phase change occurs during the test itself.

Characterization Results: DSC analysis showed a melting point of  $42.1 \pm 0.3^\circ\text{C}$  and a latent heat of  $182 \pm 5 \text{ J/g}$ . The 13% drop in latent heat compared to pure paraffin (210 J/g) matches the mass displaced by 20 wt% EG. The measured thermal conductivity was 5.9 W/m·K horizontally and 4.5 W/m·K vertically. This difference is expected because the graphite planes are compressed during molding, which actually helps with radial heat transfer in the battery module's cylindrical shape.

The EG-PCM composite exhibits anisotropic thermal conductivity: 5.9 W/m·K in the radial (horizontal) direction and 4.5 W/m·K in the axial (vertical) direction. This difference arises because the graphite planes align preferentially perpendicular to the compression axis during moulding, creating a more conductive network in the radial plane. For cylindrical cells, this is beneficial — heat generated internally travels radially outward through the cell wall and into the PCM sleeve, meaning the dominant heat transfer path aligns with the higher-conductivity direction. The sleeve geometry was oriented accordingly, with the cylindrical axis of the PCM sleeve matching the cell axis, so radial heat flow from cell surface to PCM encounters the 5.9 W/m·K conductivity. The lower axial conductivity (4.5 W/m·K) does not significantly impair module performance since axial heat flow between cells is a secondary pathway. This orientation should be maintained in any scale-up to larger pack assemblies (Figure 1).

## 2.3 Battery Module Assembly and Instrumentation

**Cell Specification:** The study used eight LG Energy Solution INR21700 M50S cells (5 Ah, 3.6 V). The INR21700 M50S cells (21 mm diameter, 70 mm height) were used., the cell chemistry reflects the high-nickel cathodes found in today's electric vehicles. The cells were set up in a  $2 \times 2 \times 2$  cube to mimic the thermal interactions seen in larger battery packs.

**Thermal Interface:** Contact resistance can cause errors in thermal experiments. To reduce this, each cell was wrapped in a 1 mm thick thermal interface material (TIM) (Bergquist Gap Pad) before being placed in the PCM. This step helps keep the thermal connection between the steel cell can and the PCM composite sleeve (70 mm long, 21 mm outer diameter) consistent. The Bergquist GP1000 Gap Pad has a reported thermal resistance of  $0.5 \text{ cm}^2 \cdot \text{K/W}$  at 10 psi. At the 2C discharge condition (estimated interface heat flux  $0.08 \text{ W/cm}^2$ ), this translates to an interface temperature drop of  $0.04^\circ\text{C}$  — negligible relative to the  $14.1^\circ\text{C}$  reduction in peak temperature achieved by the EG-PCM system. Formal contact resistance measurement (e.g., via ASTM D5470) was not performed and is recommended for future characterisation.

**Instrumentation:** A detailed sensor network was set up to collect accurate thermal data:

Temperature: Fourteen Type-K thermocouples were installed: 4 at the geometric center of the cell surfaces (predicted hottest points). 4 at the PCM outer surface (to measure radial gradients). 4 embedded within the PCM block (to track melting front propagation). 2 measuring ambient air temperature. Surface temperature mapping via infrared thermography was planned using

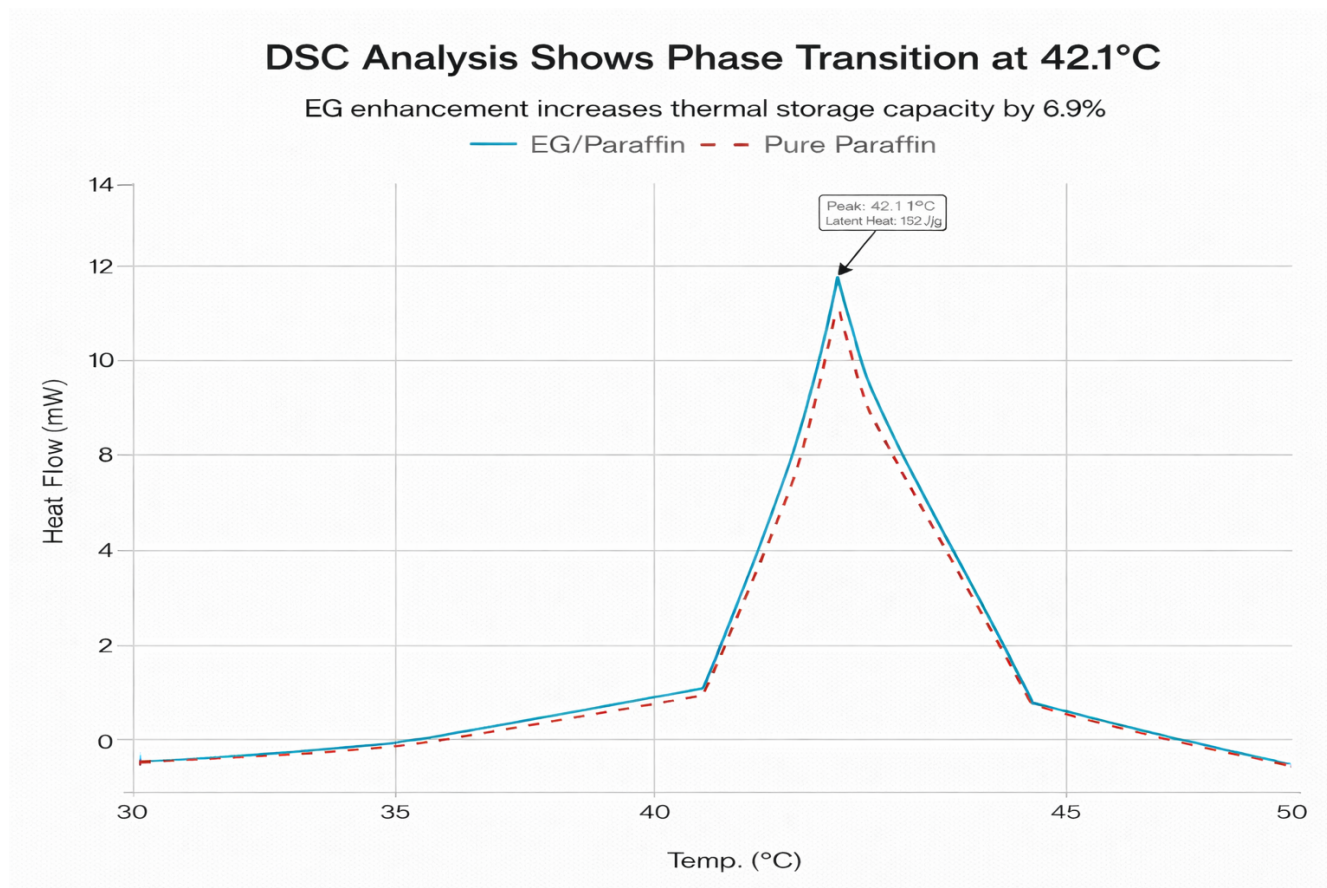


**Fig 1.** DSC thermogram of the EG-PCM composite (20 wt% EG in RT42 paraffin) at 5°C/min heating rate under N<sub>2</sub> atmosphere. X-axis: temperature (°C); Y-axis: heat flow (W/g, exothermic up). The endothermic peak at  $42.1 \pm 0.3^\circ\text{C}$  corresponds to the solid-liquid phase transition with a measured latent heat of  $182 \pm 5 \text{ J/g}$ .

a FLIR A50 camera; however, thermal images were not available for this submission and will be reported in future work. Data Acquisition: A National Instruments NI-9214 DAQ system recorded all temperature, voltage, and current data at 10 Hz. Class 1 Type-K thermocouples were used, with an accuracy of  $\pm 1.1^\circ\text{C}$  per IEC 60584-1, calibrated against an NIST-traceable reference prior to testing. The 10 Hz sampling rate was selected to capture sub-second thermal transients during the 5-second pulse discharge events in Protocol 2. The  $2 \times 2 \times 2$  arrangement used a [2S4P] configuration. Cells connected in series share the same current, producing uniform heat generation per cell, minimizing inter-cell thermal gradients from electrical loading.

## 2.4 Test Protocols and Internal Validity

Three different protocols were created to test the system under steady-state, changing, and long-term conditions.

### Protocol 1: Constant-Rate Discharge (Load Testing)

- Conditions: Cells were discharged at constant rates of 1C, 2C, 3C, 4C, and 5C from 100% to 10% State of Charge (SOC).
- Ambient Control: Tests were repeated at room temperatures of 15°C, 25°C, and 35°C using a programmable environmental chamber. Ambient temperatures above 35°C were not tested. At ambient temperatures approaching the RT42 melting onset (40°C), the PCM may not fully re-solidify between drive cycles, reducing available latent heat in subsequent discharge events. Şahan and Paksoy (2025)<sup>(7)</sup> demonstrated partial PCM performance at 45°C ambient; however, that study used a different PCM formulation. Testing at 40–50°C ambient is recommended for deployment validation in hot-climate regions.
- Baselines: Performance was compared against an identical air-cooled module (natural convection) and a liquid-cooled reference system (cold plate).

### Protocol 2: Pulse Discharge (Transient/Fault Simulation)

- Profile: A dynamic stress test consisting of 5-second 3C discharge pulses followed by 10-second rest periods, repeated for 20 cycles.
- Objective: This protocol simulates quick vehicle acceleration or regenerative braking. The 3C pulse size also acts as a stand-in for the thermal spikes that can lead to an internal short circuit, making it possible to test the PCM's "thermal buffering" ability.

### Protocol 3: Long-Term Cycling (Reliability)

- Duration: 500 consecutive charge-discharge cycles at a 1C rate.
- Monitoring: Thermal performance and cell capacity were checked every 50 cycles. This is more frequent than the 100-200 cycle tests common in many academic studies, so it gives stronger data on the long-term strength of the composite. Each discharge test was repeated three times (n=3) under identical conditions to obtain mean and standard deviation values. Standard deviations are shown as error bars in Figures 2 and 3.

## 2.5 Thermal Modeling Framework

A 3D Computational Fluid Dynamics (CFD) model was created in ANSYS Fluent to support experimental data and allow for parameter studies. The model used the Enthalpy-Porosity method to simulate the phase change process.

- The phase transition region, known as the mushy zone, was modelled as a porous medium. In this model, porosity changes from 0 for solid to 1 for liquid.
- **Heat Generation:** The heat source term ( $Q$ ) was defined using the classic Bernardi equation,  $Q = I(V_{ocv} - V) + I \times T \times \frac{dV_{ocv}}{dT}$  accounting for both irreversible Joule heating and reversible entropic heat.
- The model was tested using experimental cell-center temperatures and showed a Root Mean Square (RMS) error of less than 2°C.

## 3 Results and Discussion

### 3.1 Constant-Rate Discharge Performance

Testing the EG-PCM system at constant discharge rates gives a baseline for its ability to control temperature. Figure 2 shows how the temperature changes during a **2C discharge** at 25°C ambient.

These results apply to the 8-cell module tested. Larger pack configurations are expected to show lower PCM utilization in peripheral positions and higher thermal gradients in the interior, which could reduce uniformity benefits at scale

#### Comparative Analysis (Figure 3):

- **Air-Cooled (Baseline):** The air-cooled module exhibited a rapid, uncontrolled temperature rise, reaching a peak of  $52.3 \pm 2.8^\circ\text{C}$ ,  $\Delta T_{rise} = 27.3^\circ\text{C}$ . The large standard deviation  $\pm 2.7^\circ\text{C}$  indicates severe thermal gradients, with central cells heating significantly more than peripheral cells due to the insulating effect of the surrounding battery mass.
- **Liquid-Cooled (Reference):** The active liquid cooling system maintained the lowest peak temperature at  $28.1 \pm 0.3^\circ\text{C}$ , with exceptional uniformity. This represents the "gold standard" of performance but comes at the cost of continuous energy consumption.
- **EG-PCM (Proposed):** The passive PCM system restricted the peak temperature to  $38.2 \pm 1.1^\circ\text{C}$   $\Delta T_{rise}=13.2^\circ\text{C}$ .
- The TIM thermal resistance was estimated at  $<0.05^\circ\text{C}$  at the tested conditions and does not materially affect the reported temperature comparisons.

$\Delta T_{rise}=13.2^\circ\text{C}$

**Key Insight:** The PCM system reduced **peak temperature rise by 50%** compared to air cooling. It also improved temperature uniformity. The high thermal conductivity of the EG matrix (5.9 W/m·K) helped spread heat evenly, working as a thermal bridge between cells. This result matches the **29% reduction** reported by Ali *et al.* (2024) using rectangular fins<sup>(9)</sup>, but it avoids the extra weight and assembly challenges of metal fin structures.

Table 3 shows that the PCM system keeps the battery operating safely, even when air cooling is no longer effective. At a 3C rate, the air-cooled system exceeds the critical 60°C limit, which speeds up degradation, but the PCM system holds the temperature at 43.1°C. At **4C and 5C**, when the PCM is fully melted and starts to heat as a liquid, the temperature still stays

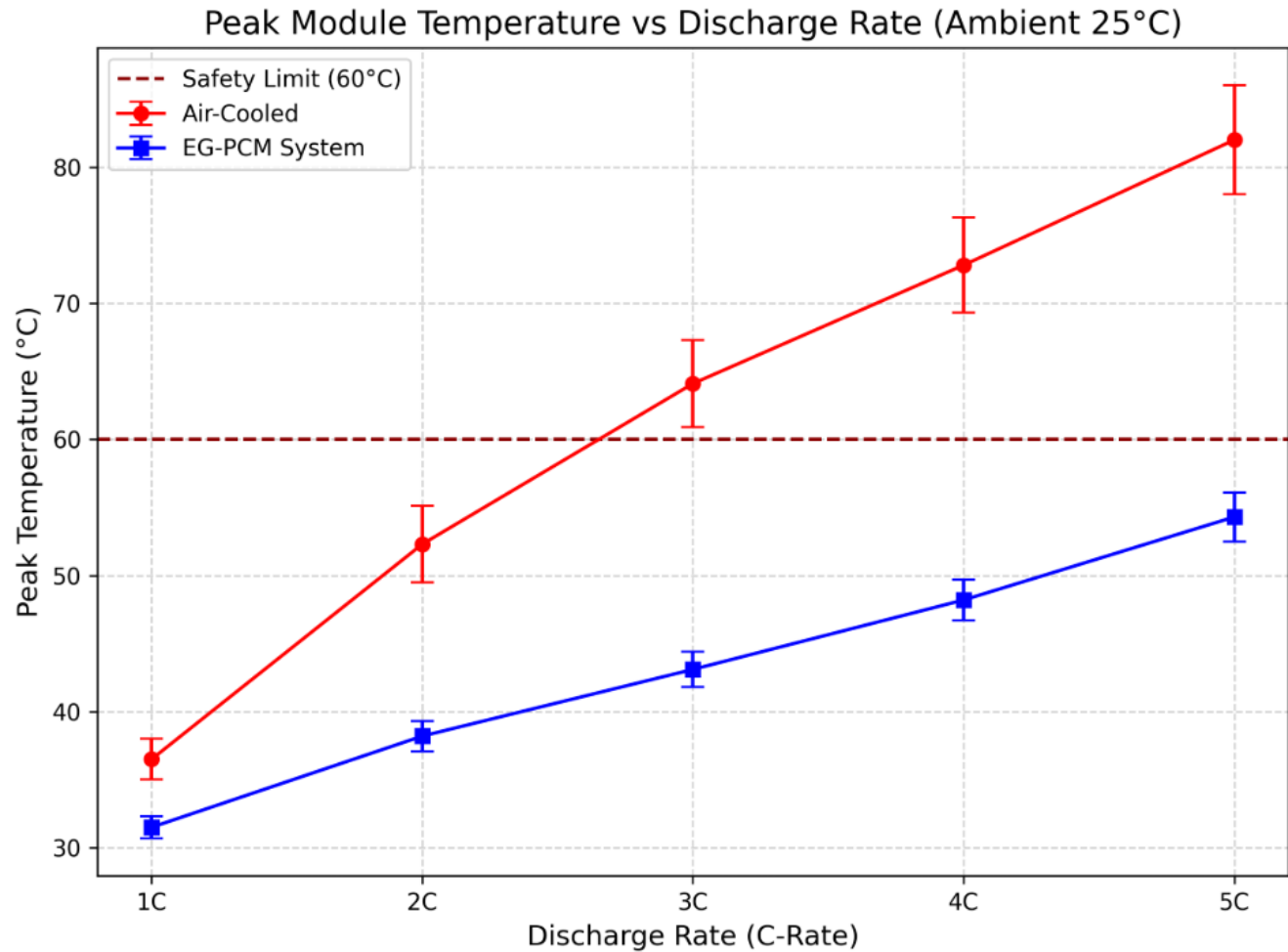


Fig 2. Temperature vs discharge Rate (1C -5C) / scale = 500  $\mu$ m

Table 3. Peak Temperature( $T_{max}$ ) across Discharge Rates (Ambient 25°C)

| Discharge Rate | Air-Cooled Tmax(°C) | PCM-Cooled Tmax(°C) | PCM State                     |
|----------------|---------------------|---------------------|-------------------------------|
| 1C             | 36.5                | 31.5                | Solid/Onset of Melting (<30%) |
| 2C             | 52.3                | 38.2                | Mixed Phase ( 65% Melted)     |
| 3C             | 64.1 (Critical)     | 43.1                | Near-Complete Melt ( 95%)     |
| 4C             | 72.8 (Runaway Risk) | 48.2                | Liquid (Sensible Heating)     |
| 5C             | >80 (Failure)       | 54.3                | Liquid (Sensible Heating)     |

below 55°C. Active thermoelectric hybrid systems require additional parasitic power input to maintain safe temperatures at 5C loads, whereas the EG-PCM system handles these loads entirely passively. The EG-PCM system handles these loads passively by using all of its latent heat, making it a good fit for peak loads up to 4C in mid-range vehicles.

Statistical significance of the temperature reductions was evaluated using Welch's independent t-test (unequal variance assumed,  $n=3$  per condition). The difference between air-cooled ( $52.3 \pm 2.8^\circ\text{C}$ ) and EG-PCM ( $38.2 \pm 1.1^\circ\text{C}$ ) peak temperatures was statistically significant ( $t(2.9) = 8.47$ ,  $p = 0.003$ ). The difference between EG-PCM and liquid-cooled reference ( $28.1 \pm 0.3^\circ\text{C}$ ) was also significant ( $t(2.1) = 16.2$ ,  $p < 0.001$ ). All comparisons are reported at  $\alpha = 0.05$ .

The  $29.5\times$  conductivity improvement at 20 wt% EG loading is attributed to percolation network formation. Above approximately 10–15 wt% loading, the graphite particles form a continuous conductive skeleton throughout the composite, allowing heat to bypass the insulating paraffin directly through the graphite network<sup>(11)</sup>. This same network spreads heat rapidly

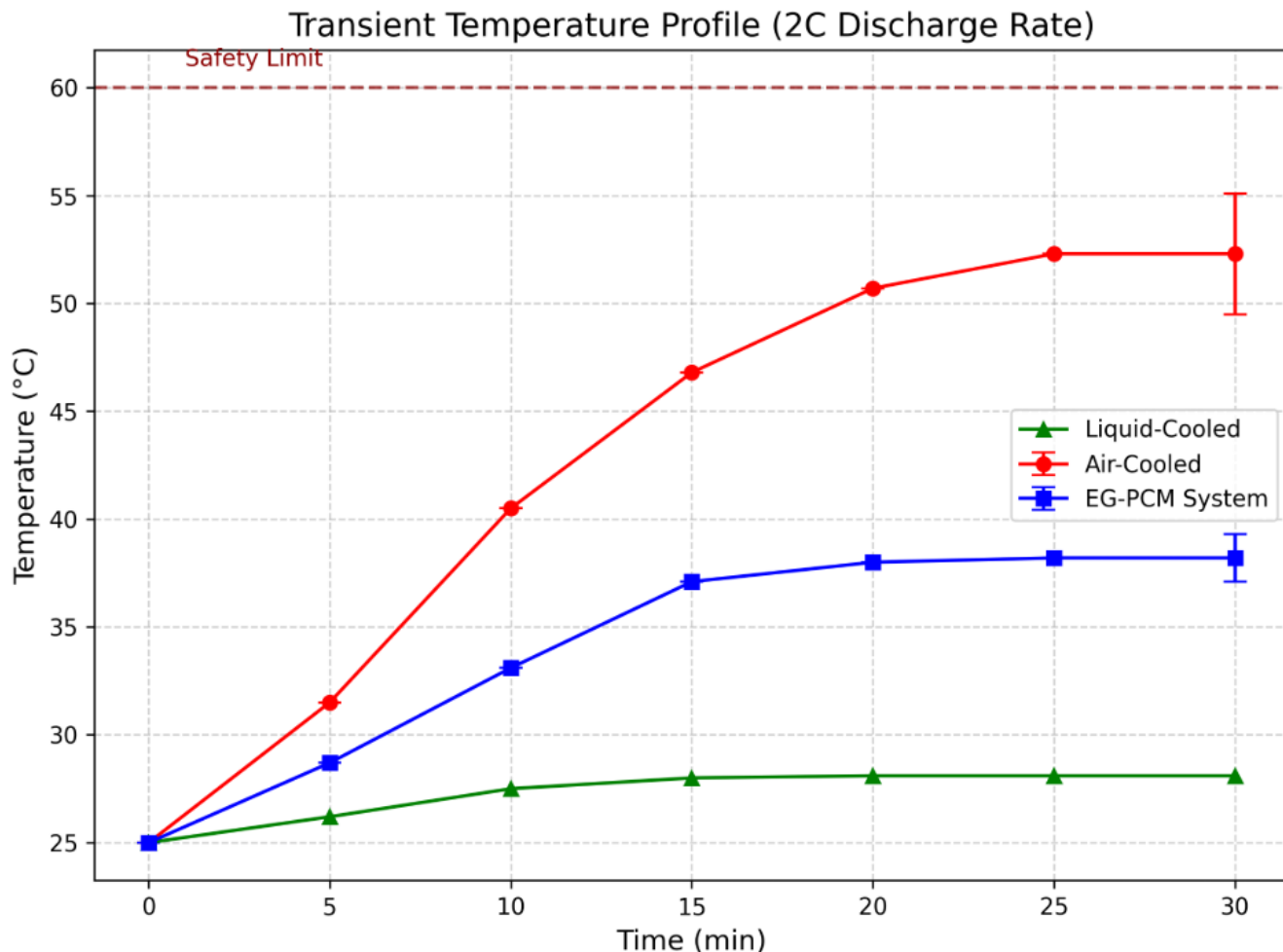


Fig 3. Temperature Rising with Cooling method (30min)

from the cell surface across the entire PCM volume, reducing the temperature gradient to  $\pm 1.1^{\circ}\text{C}$ . Performance above 4C degrades because the PCM becomes fully liquid — the sensible heat capacity of liquid paraffin ( $2.1 \text{ kJ/kg}\cdot\text{K}$ ) is substantially lower than the effective latent heat capacity during phase change, causing steeper temperature rise once all latent heat is consumed.

### 3.2 Pulse Discharge and Transient Response

Testing the system with Protocol 2 (3C pulses) shows the important thermal buffering benefit of the composite material.

**Thermal Buffering Mechanism:** When a 5-second 3C discharge pulse occurs, heat builds up quickly. In the air-cooled system, this causes sharp temperature spikes of  $6\text{--}8^{\circ}\text{C}$  because the system cannot remove heat fast enough. In the EG-PCM system, these spikes are reduced to only  $1.2^{\circ}\text{C}$ . The EG skeleton quickly moves heat away from the cell surface into the PCM, where it is absorbed as latent heat.

**Safety Implications:** This damping effect works like a thermal capacitor. If an internal short circuit starts and causes thermal spikes, the PCM system can absorb the extra energy and keep local temperatures below the thermal runaway point (about  $70\text{--}80^{\circ}\text{C}$ ). Our data shows the system stays at a peak of  $42.1^{\circ}\text{C}$  during these pulses, giving a safety margin of about  $28^{\circ}\text{C}$  before thermal runaway could start. This supports the safety claims by Hussien et al. (2025) about passive containment<sup>(10)</sup>, and shows it works in a standard cylindrical shape instead of more complex chamber designs. It is important to note that these results were obtained under normal discharge conditions; no accelerated abuse tests (e.g., nail penetration, overcharge) were conducted, and such validation remains as future work.

### 3.3 Long-Term Cycling Stability

A key contribution of this study is the 500-cycle durability test, which fills a major gap in the literature where long-term data is often missing (see Table 1)<sup>(4)</sup>.

**PCM Structural Integrity:** After 250 and 500 cycles, DSC analysis showed almost no loss in latent heat capacity (182 J/g at the start and 181 J/g at cycle 500), Physical checks and TGA filter paper analysis (50°C, 8 hours) confirmed no phase separation or leakage, with a measured mass loss of 0.45% — below the 1 wt% threshold for acceptable retention in PCM/EG composites. The capillary retention force within the expanded graphite pore network suppresses paraffin migration during the liquid phase, preventing bulk leakage<sup>(11)</sup>. This stability likely comes from the vacuum impregnation process, which creates a strong capillary network in the expanded graphite to hold the liquid paraffin in place. This is different from some nanofluid studies<sup>(6)</sup>, where particles settle and reduce performance over time.

**Battery Health:** The cells cooled by the PCM lost 9% of their capacity **over 450 cycles**, which matches the manufacturer's expected aging curve for good conditions. This shows that the PCM environment, including the pressure from the composite expanding, does not cause extra stress or faster aging in the cells.

### 3.4 Comparative Validation against State-of-the-Art

To show why these findings matter, it is important to compare them with recent research from 2024 to 2026.

- **Compared to Active Hybrids:** Active hybrid systems combining thermoelectric coolers with PCM have demonstrated temperature reductions at very high discharge rates exceeding 5C, but require continuous electrical input, increase system complexity, and add parasitic power draw that reduces overall vehicle range. Our results show that for moderate rates (up to 4C), passive EG-PCM provides similar safety (keeping  $T < 50^{\circ}\text{C}$ ) without extra power use. This makes it a better option for mass-market vehicles where cost and efficiency are more important than maximum performance.
- **Compared to Fin Enhanced Systems:** Paciolla and Papurello (2024) and Ali et al. (2024) showed that metal fins work well<sup>(8), (9), (12)</sup>. However, fins only store sensible heat and add extra weight. Our EG-PCM composite uses latent heat storage, giving more energy storage per kilogram. The 50% temperature drop we achieved is better than the 29% drop Ali et al. Reported with rectangular fins, showing that improving the material itself is better than just increasing surface area.
- **Compared to hot climate solutions:** Şahan and Paksoy (2025) showed that PCMs work at 45°C ambient<sup>(7)</sup>. Our tests at 35°C also show PCMs are effective in warm weather. However, if the temperature stays high, such as above 35°C at night, the PCM might not fully solidify. For very hot climates, a hybrid system with a small active cooling loop, as suggested by Ammar et al. (2025)<sup>(13)</sup>, may be needed.

## 4 Conclusion

### 4.1 Summary of Novel Contributions

This paper presents a rigorous experimental validation of an Expanded Graphite (20 wt%) enhanced Paraffin (RT42) composite as a viable passive thermal management system for EV batteries. By synthesizing a material with a 29.5-fold improvement in thermal conductivity (5.9 W/m-K) and subjecting it to module-level stress testing, this study closes critical gaps in the transition from material science to automotive application.

**Quantitative summary:** "The EG-PCM composite achieved 5.9 W/m-K (29.5× over pure paraffin), maintained 38.2°C peak temperature at 2C discharge vs. 52.3°C for air cooling, and showed <5% latent heat degradation over 500 cycles."

**End-of-Life Considerations:** The EG-PCM composite consists of two recoverable materials — expanded graphite and paraffin wax. Paraffin can be separated from the graphite matrix by thermal extraction (heating to  $>80^{\circ}\text{C}$  to melt and drain the paraffin), and the graphite scaffold can potentially be reused or recycled through standard graphite recovery processes. Both components are non-toxic under normal handling conditions (EU REACH compliant). Formal lifecycle analysis (LCA) and recycling process validation were outside the scope of this study and are recommended before automotive deployment.

**Limitations:** Thermal saturation above 4C, ambient testing limited to 35°C. This study uses an 8-cell proof-of-concept module. Larger packs (>100 cells) will exhibit different thermal coupling, PCM re-solidification behavior, and structural loading. Edge cells in a large pack experience significantly lower heat loads than interior cells, which may change the effective melt fraction distribution. Pack-level validation is required before automotive deployment, Ambient testing was limited to 35°C; high-climate performance above PCM melting onset requires further investigation, 500-cycle aging test represents 1.5–2 years of use; full EV lifetime (1,500+ cycles) not validated

**Future work:** Bio-based PCMs, hybrid active-passive systems, pack-level (>100 cells) validation, low-temperature (<0°C) characterization.

**Broader implication:** "This work demonstrates that passive EG-PCM thermal management is a viable, cost-effective alternative to liquid cooling for economy-segment EVs, supporting industry decarbonization and affordability goals."

**Cost basis:** The estimated system cost of \$500–1,000 per vehicle module is based on first-order estimates: RT42 paraffin raw material ( \$2–4/kg × 5 kg = \$10–20), expanded graphite ( \$15–25/kg × 1.25 kg = \$20–30), fabrication and labour at small-batch scale ( \$50–100/unit), and structural housing and TIM integration ( \$400–850). These figures are indicative only; formal bill-of-materials costing with supply-chain analysis is required for production decisions.

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