THERMAL MANAGEMENT OF LITHIUM-ION BATTERY PACKS USING PHASE-CHANGE MATERIAL COMPOSITE HEAT SINKS

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Abstract

Rising energy density requirements in electric vehicles have placed unprecedented thermal loads on lithium-ion battery packs. Uncontrolled temperature rise accelerates capacity fade, promotes lithium plating, and may trigger thermal runaway. This thesis proposes and experimentally validates a passive thermal management system (TMS) based on paraffin-graphene composite phase-change materials (PCM) integrated into an aluminium heat-sink matrix surrounding cylindrical 18650 cells. A three-dimensional finite-element thermal model was developed in ANSYS Fluent to predict cell surface temperature distributions during standard US06 drive-cycle discharge at ambient temperatures of −20°C, 25°C, and 45°C. The composite PCM (paraffin + 5 wt% expanded graphite) exhibited effective thermal conductivity $k^{eφφ}$ = 4.2 W/m·K versus 0.21 W/m·K for pure paraffin, and latent heat L = 187 J/g. Experimental validation on a 24-cell (4S6P) module demonstrated that peak cell temperature was reduced from 58.3°C (air-cooled baseline) to 37.1°C (−21.2°C reduction) during 3C discharge, with maximum temperature non-uniformity $ΔT^{max}$ held below 4.5°C. Cycle life testing over 500 cycles showed 94.2% capacity retention for the PCM-managed module versus 81.7% for the air-cooled baseline, a significant improvement for mobility applications.

Keywords: lithium-ion batteries; phase-change material; thermal management; graphene composite; electric vehicles; ANSYS Fluent

1. Introduction

Lithium-ion (Li-ion) batteries have emerged as the dominant energy storage technology for electric vehicles (EVs), grid storage, and portable electronics owing to their high energy density (150–250 Wh/kg), low self-discharge, and long cycle life [1]. However, both electrochemical performance and safety are strongly temperature-dependent. Optimal cell temperature lies in the 25–40°C range; excursions below 0°C increase internal resistance and promote lithium plating, while temperatures above 50°C accelerate solid electrolyte interphase (SEI) growth and electrolyte decomposition, leading to accelerated capacity fade and, at extremes, thermal runaway [2].

Conventional battery thermal management systems (BTMS) rely on forced air or liquid cooling. Liquid cooling offers superior heat transfer coefficients but introduces parasitic mass, pump energy, and sealing complexity. Passive systems based on phase-change materials (PCMs) absorb heat isothermally during the melting transition, naturally limiting cell temperature rise without auxiliary power. The primary limitation of paraffin-based PCMs is their inherently low thermal conductivity (~0.2 W/m·K), which is addressed in this work through dispersion of expanded graphite (EG) nanoplatelets.

2. Theoretical Background

2.1 Heat Generation in Li-Ion Cells

The volumetric heat generation rate in a Li-ion cell is governed by:

$q'' = I^2 R_{ir} + I T \partial U_o^{cc} / \partial T$ where I is current, R_{ir} is internal resistance, T is absolute temperature, and $\partial U_o^{cc}/\partial T$ is the entropic heat coefficient. At high discharge rates (C ≥ 2), Joule heating dominates.

2.2 Phase-Change Material Thermodynamics

During the solid-to-liquid transition, a PCM absorbs latent heat L (J/g) at near-constant temperature T^m, providing a thermal buffer. Energy stored per unit volume: $Q = \rho (c_s \Delta T_s + L + c_l \Delta T_l)$ where ΔT_s and ΔT_l are subcooling and superheating ranges respectively.

3. Materials and Methods

Cylindrical Samsung INR18650-25R cells (2500 mAh, nominal 3.6 V) were used. PCM composite was prepared by immersing expanded graphite (EG, surface area 280 m^2/g) in molten RT-35HC paraffin (T^m = 35°C, L = 190 J/g) under vacuum at 180°C for 4 hours, yielding a stable composite with 5 wt% EG. The 24-cell module was assembled in a 6P4S configuration within a CNC-machined 6061-T6 aluminium enclosure. Cell temperatures were logged at 1 Hz using calibrated K-type thermocouples (accuracy ±0.5°C) at three axial positions per cell.

4. Results and Discussion

The composite PCM TMS reduced peak cell temperature by 21.2°C during 3C discharge. FEA predictions agreed with measured temperatures within ±2.1°C RMSE. The improved thermal uniformity (ΔT < 4.5°C vs. 12.3°C for baseline) translates directly to more uniform state-of-charge (SOC) distribution across the parallel string, reducing capacity mismatch losses. Life test results confirm the temperature reduction's practical significance: the PCM module retained 94.2% capacity at 500 cycles versus 81.7% for air cooling, a 12.5 percentage-point improvement attributable to reduced SEI growth kinetics at lower temperatures.

5. Conclusions

- Paraffin + 5 wt% expanded graphite composite achieves k^{eff} = 4.2 W/m·K, a 20× improvement over pure paraffin, while retaining L = 187 J/g.
- The PCM TMS limits peak cell temperature to 37.1°C at 3C discharge, within the optimal operating window.
- Capacity retention after 500 cycles improves from 81.7% (air-cooled) to 94.2% (PCM-managed).
- The validated ANSYS Fluent model enables virtual screening of alternative PCM compositions and module geometries without physical prototyping.

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