integrated CFD–RSM approach provides both qualitative flow-thermal insights and quantitative design guidelines, enabling efficient BTMS optimization for varying load conditions while balancing safety, uniformity, and energy efficiency.

Keywords:

Air-cooled BTMS, 21700 lithium-ion battery, finned heat sink, thermal, management optimization, CFD–RSM integration, multi-response ANOVA.

Design and Multi-Objective Optimization of Fin-Assisted Air-Cooled Thermal Management System for 21700 Lithium-Ion Cylindrical Cells Using Numerical Simulation and Response Surface Methodology

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Abstract:

This study presents a comprehensive numerical and statistical investigation of an air-cooled BTMS for a single 21700 cylindrical lithium-ion cell, focusing on the influence of airflow velocity, discharge rate (C-rate), and longitudinal fin configuration. A 3D CFD model, validated against experimental data, was developed to evaluate four configurations (bare cell, 2 fins, 4 fins, 6 fins) under velocities of 2–6 m/s and C-rates of 1C–3C. The analysis assessed peak temperature (Tmax), temperature difference (ΔT), and average temperature (Tavg) to determine thermal safety and uniformity. Results indicate that C-rate is the dominant factor, with Tmax rising from 30 °C at 1C to over 100 °C for the bare cell at 3C–2 m/s. Increasing airflow from 2 m/s to 6 m/s reduced Tmax by up to 15 °C at high C-rates, while adding fins improved heat spreading, lowering Tmax by 8–10 °C and ΔT by up to 4 °C compared to the bare cell. At 3C–6 m/s, a 6-fin configuration achieved Tmax ≈60 °C and ΔT < 8 °C, ensuring safe operation. Velocity streamline and temperature contour analyses revealed that fins enhance circumferential flow coverage, reduce recirculation zones, and improve thermal uniformity. Response Surface Methodology (RSM) models for Tmax , ΔT, and Tavg achieved R2 > 0.97, with ANOVA confirming significant main and interaction effects. Multi-response optimization identified an optimal low-load condition (2 m/s, 1C, 2 fins) yielding Tmax = 39.16 °C, ΔT = 6.78 °C, and Tavg = 32.08 °C (desirability = 0.798). At high C-rates, optimal thermal performance required ≥ 4 fins and ≥ 4 m/s airflow. The