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Electro-Thermal-Electromagnetic Model-Based Immersion Cooling Channel Design for Large Pouch Lithium-Ion Batteries

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Extended Abstract

Immersion cooling for lithium-ion batteries has emerged as a promising thermal management technique to reduce the charging time of electric vehicles and enhance the safety under thermal runaway conditions [1][2]. However, when applied at the battery pack level, the large coolant flow cross-section leads to low velocity, which results in a reduced heat transfer coefficient and limited cooling performance. Moreover, the increased fluid volume raises the overall weight and cost of the system, making practical application challenging [3]. To overcome these issues, it is necessary to design an optimized flow path that concentrates coolant in areas with high heat dissipation performance and minimizes cooling in less critical regions, thereby reducing total coolant volume while maintaining thermal efficiency [4][5].

This study aims to propose an electro-thermal coupled model and an electromagnetic model capable of quantitatively calculating the heat generation and dissipation in large-format pouch cells for vehicle applications. Based on the proposed modeling, the cooling efficiency was ranked by region and the flow was concentrated in high-efficiency areas, leading to an optimized immersion cooling channel design that reduces fluid volume and enhances flow velocity.

To accurately represent the cooling effect of the cell casing and the heat generation of tabs, the cell is divided into casing, stack, and tabs, and implemented as a 3D CFD model. The cell stack is modeled with an equivalent circuit model (ECM), and the heat generation of tabs was incorporated via an electromagnetic model to improve accuracy over previous studies.

Cell charge/discharge experiments were conducted to validate the model under natural convection conditions at 0.5C to 2C-rates across SOC 0–100%, and the performance of the proposed model was compared with that of a conventional lumped model. The 3p4s module was then analyzed under immersion cooling conditions, and regional heat transfer was calculated to prioritize the cooling needs. CFD analysis was performed using STAR-CCM+ software with prism layer meshing and the k-epsilon turbulence model.

In the 2C discharge case with the largest error, the average relative error for surface temperature, tab temperatures (positive and negative), and voltage remained within 10%. Compared to the lumped model, the proposed model demonstrated better agreement, particularly in surface temperature and the negative tab region. These results confirmed the cooling effect of the cell casing and the importance of tab and busbar heat generation, validating the accuracy of the proposed model. The CFD results for the 3p4s immersion cooling module identified the following order of cooling priority: folding area, terrace including tabs and busbars, and the bottom surface. Coolant flow was concentrated on high-priority components, and improvements were confirmed in stack temperature, fluid weight, and energy density compared to the baseline design.

This study proposes and validates an integrated electro-thermal-electromagnetic model that incorporates the cooling effect of the cell casing and the heat generation characteristics of tabs and busbars. Using the proposed model, an immersion cooling channel was designed to enable effective thermal management while reducing fluid weight. Quantitative performance improvements were confirmed compared to the baseline design. This research not only contributes to improved thermal stability and extended cycle life of pouch-type battery modules by enabling precise temperature distribution prediction, but also addresses fundamental limitations of immersion cooling systems by reducing coolant mass and cost.

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