Modeling and Analysis of a Lithium-ion Convection Battery

by

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Lithium-ion batteries (LIBs), crucial to modern portable electronics and increasingly significant in transportation and grid storage, represent the state-of-the-art in energy storage technology due to their high energy density, efficiency, and long cycle life. Despite declining costs and improving energy densities, driven by advancements in materials and manufacturing processes along with expanded market scale, current LIBs often struggle to meet the evolving demands of new applications. Current research predominantly focuses on material innovations, with less attention given to re-engineering cell architectures to address the technological challenges.

This thesis investigates the "convection battery" cell architecture, a novel approach involving circulating electrolyte through the porous electrodes and separator of a LIB cell to enhance mass and thermal transport. Compared to traditional LIBs, this architecture may enhance ion flux in electrodes, improve safety and maintenance, simplify system design, and ultimately reduce overall costs. Prior studies, including experimental work in our laboratory, have highlighted the benefits of electrolyte flow, yet a comprehensive engineering analysis on this aspect is lacking.

To bridge this gap, this thesis employs a combination of modeling and analytical techniques to systematically explore the potential advantages and opportunities enabled by the convection battery cell architecture. The first half of the thesis delves into the fundamental mechanisms of electrolyte convection in enhancing mass and thermal transport within a LIB cell, utilizing a convection battery sandwich cell layer model developed from the Li-ION SIMulation BAttery (LIONSIMBA) Toolbox. Through dimensional analysis, I identified conditions under which convection provides the most performance enhancement, alongside exploring the necessary flow rates and performance limitations.

In the latter half of the thesis, practical implementation aspects are examined, starting with the requisite additional electrolyte to achieve desired transport enhancements. A potential design for the convection battery system is proposed, and COMSOL-based convection battery cell stack models and a system design model were developed to aid the analyses. Through illustrating its utility in two distinct scenarios, I have endeavored to highlight the convection battery's unique value proposition and its potential to broaden the applicability of current LIB technologies. This thesis establishes a foundation for the convection battery technology, highlighting its potential to improve the performance of current LIB systems and to venture into novel application domains. To conclude the thesis, I discuss future research avenues and the design considerations essential for the advancement and realization of the convection battery technology.

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