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Modeling of steady-state convective cooling of cylindrical Li-ion cells

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HIGHLIGHTS

- Presents a new thermal model to predict temperature rise in cylindrical Li-ion cells.
- Results are in excellent agreement with experimental data.
- Results help understand thermal runaway and other thermal issues in Li-ion cells.
- Results predict the importance of various design parameters for thermal performance.
- Results are is used to determine design guidelines for cell sizing.

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ABSTRACT

While Lithium-ion batteries have the potential to serve as an excellent means of energy storage, they suffer from several operational safety concerns. Temperature excursion beyond a specified limit for a Lithium-ion battery triggers a sequence of decomposition and release, which can preclude thermal runaway events and catastrophic failure. To optimize liquid or air-based convective cooling approaches, it is important to accurately model the thermal response of Lithium-ion cells to convective cooling, particularly in high-rate discharge applications where significant heat generation is expected. This paper presents closed-form analytical solutions for the steady-state temperature profile in a convectively cooled cylindrical Lithium-ion cell. These models account for the strongly anisotropic thermal conductivity of cylindrical Lithium-ion batteries due to the spirally wound electrode assembly. Model results are in excellent agreement with experimentally measured temperature rise in a thermal test cell. Results indicate that improvements in radial thermal conductivity and axial convective heat transfer coefficient may result in significant peak temperature reduction. Battery sizing optimization using the analytical model is discussed, indicating the dependence of thermal performance of the cell on its size and aspect ratio. Results presented in this paper may aid in accurate thermal design and thermal management of Lithium-ion batteries.

1. Introduction

A significant amount of research has been carried out in past few decades on Li-ion batteries for energy storage. Despite several advantages over other energy storage technologies such as high specific energy and energy density [1,2], the commercialization of Li-ion battery technology has been slower than expected due to risks associated with high temperature operation and other safety-related concerns. Such concerns have been highlighted in several recent incidents where Li-ion batteries and battery packs have been found to be responsible for fire aboard aircraft [3,4]. These incidents underscore the importance of developing a fundamental understanding of thermal characteristics of Li-ion cells, particularly the capability of temperature prediction during the operation of a cell.

Similar to any other energy storage device, charging or discharging a Li-ion battery results in heat generation and thus increase in temperature due to exothermic electrochemical reactions and Joule heating [5,6]. Heat generation rate is known to be a function of depth-of-discharge, temperature and the rate at which a cell is charged or discharged, often referred to as C-rate [7].

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There are severe limitations to temperature rise permitted in a Li-ion cell, particularly for military applications with high reliability requirements. Thermal runaway at high temperature is a well-known problem in Li-ion batteries [8,9]. While a small temperature rise is known to actually improve performance due to reduced impedance [10], larger temperature rise results in a series of exothermic mechanisms including decomposition of the Solid-Electrolyte Interface (SEI) [11,12] and short circuit due to separator layer rupture from dendrite formation, which ultimately leads to catastrophic failure [8]. As a result, Li-ion cells must operate in a very narrow temperature window. In addition to absolute temperature rise, spatial uniformity of the temperature field is also desirable [13], since this prevents imbalance of temperature-dependent electrochemical reaction rates within the cell or battery pack.

Despite the clear importance of thermal management of cylindrical Li-ion batteries, only a limited amount of literature is available on thermal management and cooling of Li-ion batteries. Only a few studies have reported measurement of thermophysical properties such as thermal conductivity and heat capacity of Li-ion cells [12,14]. Early work in this direction did not recognize the strong anisotropy in thermal conduction in a Li-ion cell. Recent measurements have reported a method for rapid measurement of anisotropic thermal conductivity as well as heat capacity of a Li-ion cell [14]. These measurements indicate nearly two orders of magnitude difference in the radial and axial thermal conductivities of a Li-ion cell [14]. At the battery pack level, some work has been reported on thermal simulations of cooling strategies for Li-ion cells [15,16]. The use of solid-to-liquid phase change materials embedded around cells in a battery pack [17], as well as two-phase flow interstitially within the cell [18] has been proposed for absorbing heat and reducing peak temperature rise. However, such an approach leads to reduced energy density since the phase change material does not store electrochemical energy and results in more complicated cell design. It is important to determine the limits of air/liquid based convective cooling approaches [7] and to develop a sound theoretical framework to understand the dependence of temperature rise in a convectively cooled Li-ion cell on various parameters, such as geometry, cooling parameters, etc. A first step towards effective thermal management of Li-ion cells is the capability to accurately model and predict temperature fields within an operating cell. The temperature field resulting from the heat generation depends on a variety of parameters including geometry, material properties, etc. and needs to be modeled accurately. A number of models are available for predicting volumetric heat generation rates as a function of electrical operating parameters of the cell, ranging from very simple, assuming uniform heat generation rate [5] to very sophisticated [9,13]. Some papers also model volumetric heat generation as a space dependent parameter, accounting for Joule heating that occurs primarily at the two current collector tabs, resulting in non-uniformity, particularly at high discharge rates [9]. Heat generation modeling is complicated by the fact that heat generation may vary with time in specific applications if the charge/discharge rate changes [6]. For example, in an electric vehicle, changes in demand on the battery due to vehicle acceleration and other factors may result in the heat generation rate being a function of time.

In contrast to heat generation modeling, limited work has been reported on temperature field prediction [9,19–24], which is a more critical parameter for safety and performance considerations. While these models provide a basis for temperature prediction, there are several shortcomings. Many past models are one-dimensional [20] and do not account for the spirally-wound geometry of a cylindrical Li-ion cell, boundary conditions encountered in realistic applications, or the thermal conduction anisotropy in a cylindrical cell. Several thermal models of a Li-ion cell reported in the recent past treat the cell as a lumped body with a single temperature [20,21], which may not be an appropriate assumption for most applications. Three-dimensional thermal models for a Li-ion cell have been presented [22], but this model is solved numerically, and does not offer analytical, closed-form solutions for the temperature field. Some recent work accounts for the spiral nature of the electrodes in a cylindrical Li-ion cell [25], but this work neglects the axial dimension of the cell and does not present a closed-form analytical solution. Recent work has presented analytical models for temperature distribution in prismatic Li-ion cells [23,24] but these models do not readily apply to a cylindrical geometry where heat transfer characteristics are fundamentally different from a prismatic cell.

This paper presents a cell-level, steady-state analytical thermal model of a cylindrical Li-ion cell being cooled on the outside surface by convective flow. Thermal conduction anisotropy within the cell is accounted for. Closed-form analytical solutions for both uniform and space-dependent heat generation rates are presented. The next two Sections present the analytical models, including assumptions, governing equations and closed-form solutions for the temperature field. These models are validated by comparison with experimental measurements on a thermal test cell in Section 4. Section 5 discusses a number of applications of these thermal models including thermal optimization of the convective cooling process and battery sizing. Fundamental limitations of thermal management based on convective cooling are discussed.

2. Analytical model: uniform heat generation

Consider a cylindrical Lithium-ion cell of radius R and height H shown schematically in Fig. 1. Volumetric heat generation rate Q is assumed within the cell due to electrochemical reactions and Joule heating. In this Section, Q is assumed to be spatially uniform, whereas Section 3 considers the case where Q may be a function of space. It is assumed that the outside surfaces of the cell are being cooled with heat transfer coefficients of h_r and h_z for the curved surface and the end surfaces respectively. In case one particular surface is insulated, the respective heat transfer coefficient can be set to zero. Such a situation may arise, for example when the

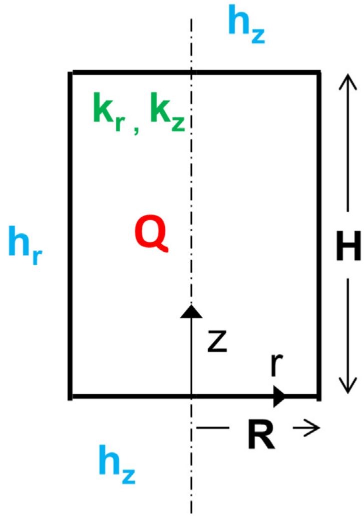

Fig. 1. Schematic diagram showing battery geometry and thermal parameters for the analytical thermal model. Q may be uniform (Section 2) or may vary radially/axially (Section 3).