

Nonuniform Heat Source Model for a Lithium-Ion Battery at Various Operating Conditions

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ABSTRACT

As battery temperature greatly affects performance, safety, and life of Li-ion batteries in plug-in and electric vehicles under various driving conditions, automakers and battery suppliers are paying increased attention to thermal management for Li-ion batteries in order to reduce the high temperature excursions that could decrease the life and reduce safety of Li-Ion batteries. Currently, the lack of fundamental understanding of the heat generation mechanism due to complex electrochemical phenomena prohibits accurate estimation of the heat generation within Li-ion cells under various operating conditions. Heat from Li-ion batteries can be generated from resistive dissipation, the entropy of the cell reaction, heat of mixing, and other side chemical reactions. Each of these can be a significant source of heat under a range of circumstances. The main purpose of the present study is to develop a practical heat source model for Li-ion batteries for HEV to help to assess the battery pack cooling performance. This paper summarizes the progress on the development and validation of the non-uniform heat source model. The temperature distributions of the battery during discharge from the heat source model were in good agreement with those from the experimental measurements at the discharge rates ranging from 0.5C to 5C.

INTRODUCTION

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under various driving conditions, automakers and battery suppliers are paying increased attention to thermal management for Li-Ion batteries in order to reduce the high temperature excursions that could decrease the life and reduce safety of Li-Ion batteries. In a battery pack the driving conditions and the type of heating and cooling could lead to an uneven temperature distribution in the pack. Uneven temperature distributions in a pack could lead to electrically unbalanced modules and, thus, lead to lower performance and shorter battery life. In order to reduce the battery temperature variation in a pack and also to achieve optimum battery temperature, heat source models for Li-Ion batteries and the subsequent computational models for the cell level and the pack level analysis are required.

Currently, the lack of fundamental understanding of the heat generation mechanism due to electrochemical phenomena prohibits accurate estimation of the heat generation within Li-ion cells under various operating conditions. Heat from Li-ion batteries can be generated from resistive dissipation, the entropy of the cell reaction, heat of mixing, and other side chemical reactions. Each of these can be a significant source of heat under a range of circumstances. It is particularly important to understand the heat generation phenomena for various cell chemistries and to predict the rate of heat generation under various cell operating conditions. Typically, battery heat source models, ranging from physics-based models to empirical models, predict cell thermal response to a given load profile, but neglect the spatial variations of temperature and electric potential distribution within the cell.

Resistive dissipation is relatively well understood. Equivalent Circuit model [1] is an empirical model to represent the battery as an ideal open circuit voltage in series with a resistor called internal resistance. This empirical model linearizes the battery behavior and fits the empirical parameters based on a test cycle, such as the Hybrid Pulse Power Characterization [2]. Equivalent Circuit model provides the uniform heat generation per cell due to Joule heating and cannot capture the heat generation due to electrochemical reactions.

It is well recognized that the heat generation from the cell is not uniform [3]. Robust thermal management design requires a more realistic cell model that properly captures the non-uniform heat generation based on electrochemical reactions. Fundamental research in the heat generation mechanism is very important for successful assessment of the Li-ion battery cell performance, the life of the battery, and the cell degradation mechanism. NREL [4] has developed a multi-scale approach that solves the cell-level heat and current transport and electrode-level lithium transport and charge transfer kinetics using separate macro- and micro-grid domains, which couples the two domain variables on a volume-averaged basis. Although NREL's multi-scale multidimensional (MSMD) model [5] accurately predicts spatial variations in cell performance, including non-uniformities of cycling, temperature, and heat generation, it requires a significant efforts and time to complete the total simulation package for the battery thermal management.

Although MSMD [5] is our ultimate goal for the battery thermal management, we still need a simpler and more practical model for the non-uniform heat source for our short term need that allows for rapid cooling simulations based on Computational Fluid Dynamics. The proposed simpler form is based on solving the electric potential distribution and current transport with a semi-empirical model to approximate the lithium transport in the electrolyte and porous media region in the electrodes. Although this model is less predictable than the MSMD model [5], it allows for design variations of the cell aspect ratios, tap location and size, and evaluation of cooling packages for a given cell chemistry and cell construction. The proposed non-uniform heat source model is practical and relatively easy to implement into the Computational Fluid Dynamics software to predict cell temperatures under various cell operating conditions.

HEAT SOURCE MODEL

A cell consisting of two parallel plate electrodes of the battery (shown in Figure 1) is chosen because the battery consists of the same repeating units of positive and negative electrode plates, polymer electrolytes and separators. In this figure, the current collecting tabs are the current collectors extending outside from the rectangular electrodes. Figure 1 shows a schematic diagram of the current flow in the cell

during discharge. The distance between the electrodes was assumed to be so small that the current flow between the electrodes would be perpendicular to the electrodes. From the continuity of current on the electrodes, the following equations can be derived:

$$\nabla \cdot \vec{i}_p - J = 0 \quad \text{in } \Omega_p \quad (1)$$

$$\nabla \cdot \vec{i}_n + J = 0 \quad \text{in } \Omega_n \quad (2)$$

where $\vec{i}_p$ and $\vec{i}_n$ are the linear current density vectors (current per unit length (A m^{-1})) in the positive and negative electrodes, respectively, and J is the current density (current per unit area (A m^{-2})) transferred through the separator from the negative electrode to the positive electrode. Ω_p and Ω_n denote the domains of the positive and negative electrodes, respectively. According to Ohm's law, $\vec{i}_p$ and $\vec{i}_n$ can be written as follows:

$$\vec{i}_p = -\frac{1}{r_p} \nabla V_p \quad \text{in } \Omega_p \quad (3)$$

$$\vec{i}_n = -\frac{1}{r_n} \nabla V_n \quad \text{in } \Omega_n \quad (4)$$

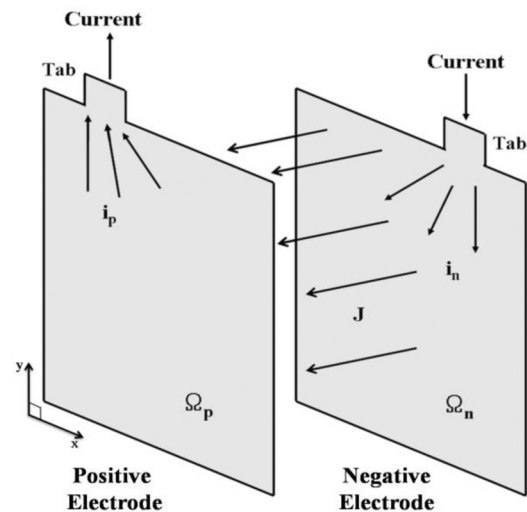


Figure 1. Schematic diagram of the current flow in the parallel plate electrodes of a battery.

where r_p and r_n are the resistances (Ω) of the positive and negative electrodes, respectively, and V_p and V_n are the

potentials (V) of the positive and negative electrodes, respectively. The following Poisson equations for V_p and V_n were obtained by substituting Equations (3) and (4) into Equations (1) and (2):

$$\nabla^2 V_p = -r_p J \quad \text{in } \Omega_p \quad (5)$$

$$\nabla^2 V_n = +r_n J \quad \text{in } \Omega_n \quad (6)$$

The relevant boundary conditions for V_p are

$$\frac{\partial V_p}{\partial n} = 0 \quad \text{on } \Gamma_{p_1} \quad (7)$$

$$-\frac{1}{r_p} \frac{\partial V_p}{\partial n} = \frac{I_0}{L} \quad \text{on } \Gamma_{p_2} \quad (8)$$

where $\partial/\partial n$ denotes the gradient in the direction of the outward normal to the boundary. The first boundary condition (7) implies that there is no current flow through the boundary (Γ_{p1}) of the electrode other than the tab. The second boundary condition (8) means that the linear current density through the tab (Γ_{p2}) of the length L (cm) is constant to the value of I_0/L . I_0 is the total current (A) through the tab in the mode of constant-current discharge. The boundary conditions for V_n are

$$\frac{\partial V_n}{\partial n} = 0 \quad \text{on } \Gamma_{n_1} \quad (9)$$

$$V_n = 0 \quad \text{on } \Gamma_{n_2} \quad (10)$$

The first boundary condition (9) implies the same as in the case of V_p . The second boundary condition (10) means that the potential at the tab of the negative electrode is fixed to the value of zero as the reference potential.

Regarding the electrode as the equivalent network of parallel-connected resistors of electrode material and current collector, the resistance, r (r_p or r_n), was calculated as follows:

$$r = \frac{1}{h_c S_c + h_e S_e} \quad (11)$$

where h_c and h_e are the thicknesses (m) of the current collector and the electrode material, respectively, and S_c and S_e are the electrical conductivities (S m^{-1}) of the current collector and the electrode material, respectively.

The current density, J , of Eqs. (5) and (6) is a function of the potential difference between the positive and negative electrodes, ($V_p - V_n$). The functional form depends on the polarization characteristics of the electrodes. In this study, the following polarization expression is adopted

$$J = Y(V_p - V_n - U) \quad (12)$$

where Y and U are the fitting parameters. U and Y are expressed as functions of the depth of discharge (DOD) as follows:

$$U = a_0 + a_1(\text{DOD}) + a_2(\text{DOD})^2 + a_3(\text{DOD})^3 \quad (13)$$

$$Y = a_4 + a_5(\text{DOD}) + a_6(\text{DOD})^2 \quad (14)$$

where $a_0 \sim a_6$ are constants to be determined experimentally at the environmental temperature of 25 °C.

By solving the equations listed previously, the distribution of the current density, J , on the electrodes can be obtained as a function of the position on the electrode and time. Therefore, the DOD varies along with the position on the electrode and time elapsed during discharge. The distribution of DOD on the electrode can be calculated from the distribution of J as follows:

$$\text{DOD} = \frac{\int_0^t J dt}{Q_T} \quad (15)$$

where t is the discharge time (s) and Q_T is the theoretical capacity per unit area (Ah m^{-2}) of the electrodes.

Based on the differential energy conservation for a battery, the transient two-dimensional equation of heat conduction can be written as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial T}{\partial y}) + q - q_{\text{conv}} \quad (16)$$

where ρ is the density (kg m^{-3}), C_p is the volume averaged specific heat capacity at constant pressure ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), T is the temperature ($^\circ\text{C}$), k_x and k_y is the effective thermal