

Validation of a Thermal-Electric Li-Ion Battery Model

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ABSTRACT

Commercial vehicle manufacturers are investing substantial resources into the development and testing of advanced battery systems for the next generation of hybrid and electric vehicles. Likewise the US army is investing in lithium ion battery research for power and energy applications including SLI (starter, lights, and ignition), silent watch, unmanned vehicles, and directed energy weapons. A major design constraint is the management of the heat generated by Li-Ion battery systems. Extreme battery temperatures impact both the performance and reliability of the battery system as well as the overall operation of the vehicle. Analysis tools that can address vehicle and battery thermal management issues are needed to accelerate this development. To meet that need, a coupled thermal-electric model for battery cells and packs has been developed and implemented into the existing thermal modeling software RadTherm. This paper documents the comparison of physical test results with a computer model of the thermal response for an actual vehicle Li-Ion battery cell.

The thermo-electrical battery model described in this paper predicts an effective driving potential and internal conductance for a cell based on the cell environmental temperature and measure of state of charge. From these parameters a local current density is computed and applied to an electrical model of the voltage distribution on the electrodes. Heat generation is derived from the local voltage difference across the electrodes and the current density between electrodes and then applied to a thermal model to predict local temperature rise over the cell.

When applied to a cell, the battery model is useful for predicting the effects of cell size, tab location, and current collector thickness on voltage distribution and local heat generation. The model can also be applied to a multi-cell pack to study the effects of various thermal management strategies. In either application, battery loads corresponding to pre-determined drive cycles can be applied to the model to evaluate the ability of a particular cell or pack design to supply vehicle power in a given operating scenario. In this paper we describe the implementation of the model, compare model predictions to electrical and thermal measurements taken on a test cell, demonstrate the effects of different cell configurations on voltage and temperature distributions, and show the relative effectiveness of various cooling schemes (natural and forced air convection and edge cooling) applied to a pack.

CITATION: Peck, S., Olszanski, T., Zanardelli, S. and Pierce, M., "Validation of a Thermal-Electric Li-Ion Battery Model," *SAE Int. J. Passeng. Cars - Electron. Electr. Syst.* 5(1):2012, doi:10.4271/2012-01-0332.

INTRODUCTION

The automotive industry as well as the Army is in the process of developing alternative power and energy sources for vehicles and other military applications. There is a growing interest in electric or hybrid electric vehicles employing batteries to provide part or all of the energy needed for motive power. Because batteries generate heat when charged or discharged, and their performance

parameters depend on their operating temperature, there is a need for robust thermal management systems dedicated to the battery. The design of these systems requires modeling tools capable of simulating the interaction of a battery with the power and thermal management subsystems in the vehicle.

Many OEMs and component suppliers use a general thermal analysis code called RadTherm[1] for thermal simulation and design assessment. A battery module has been added to RadTherm to facilitate modeling of the electrical



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and thermal behavior of a battery integrated with a thermal management system. In this paper, we describe the electro-thermal model and its implementation in RadTherm, compare the model output with validation data, and give examples of how the model can be employed in modeling studies to answer thermal management design issues.

BATTERY MODEL

The electro-thermal model chosen to describe battery behavior is an empirical approach that seeks to describe the current-voltage relationship of a battery with fitting parameters that are functions of the depth-of-discharge of a cell, and the temperature of the cell. The fitting parameters are an *effective* open cell voltage, and an *effective* internal conductance of the cell. The model has been described in the literature[2,3,4]. It relates the current density passing from cathode to anode to the voltage difference from cathode to anode, thus:

$$J = Y[V_p - V_n - U] \quad (1)$$

where J is the current density, V_p the voltage on the cathode, V_n the voltage on the anode, Y is the fitting parameter representing the internal conductance of the cell, and U is the fitting parameter representing an effective open cell voltage. Note that in this formulation, a cell discharge corresponds to a negative current density.

The fitting parameters are functions of the depth of discharge and ambient temperature, thus

$$U = \sum_i \sum_j \alpha_{ij} T^j \text{DoD}^i \quad (2)$$

and

$$Y = \sum_i \sum_j \beta_{ij} T^j \text{DoD}^i \quad (3)$$

where the α_{ij} and β_{ij} are the coefficients of a polynomial curve fit of the U and Y parameters, T is the ambient or environmental temperature at which the discharge measurements were made, and DoD is the depth of discharge, defined as

$$\text{DoD} = \frac{A \int J dt}{\text{Capacity}} \quad (4)$$

A is the area of the cell, t is time in hours, and capacity is the rated capacity of the cell in ampere-hours. The order of the polynomials varies from data set to data set, but typically is 5th or 6th order in DoD , and 2nd or 3rd order in temperature.

The current is distributed to the electrodes via metallic collector plates. These collector plates have a voltage distribution on them that is described by Poisson's equation (see Figure 1). On the collector plate for the anode,

$$\nabla^2 V_n = \frac{J}{\sigma_n t_n} \quad (5)$$

where σ_n is the electrical conductivity and t_n is the total thickness of the anode collector plate.

On the cathode collector plate,

$$\nabla^2 V_p = -\frac{J}{\sigma_p t_p} \quad (6)$$

where σ_p is the electrical conductivity and t_p is the total thickness of the cathode collector plate.

The heat generation due to current transfer from cathode to anode, $\dot{q}_c'''$ is described by

$$\dot{q}_c''' = \frac{J}{t} \left[V_p - V_n - E_{oc} + T \frac{dE_{oc}}{dT} \right] \quad (7)$$

Here t is the total thickness of the cell and E_{oc} is the open cell voltage.

The product of the current and the sum of the first three terms in the brackets is the irreversible heating due to cell polarization, and is always positive (given the convention of discharge equates to negative current). The last term in brackets represents the reversible heat due to the entropy of reaction, and is positive (exothermic) for cell charging, and negative (endothermic) during cell discharge[5,6].

There is resistive heating in the collector plates, described by

$$\dot{q}_c''' = -J_c \cdot \nabla V_c = \sigma_c (\nabla V_c \cdot \nabla V_c) \quad (8)$$

Here the subscript c refers to either the anode collector (n) or the cathode collector (p).

We assume the temperature through the thickness of the cell is uniform, and is described in the other two dimensions by

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + \dot{q}_c''' - 2h(T - T_a)/t \quad (9)$$

Here, $\dot{q}_c''' = \dot{q}_c''' + \dot{q}_n''' + \dot{q}_p'''$, ρ is the average density of the cell, C the average specific heat of the cell materials, k the

average or effective thermal conductivity of the cell materials, h is the effective heat transfer coefficient between the cell surface and the ambient environment, and T_a is the effective ambient temperature. In this formulation, convection and radiation have been combined into the effective h and T_a .

IMPLEMENTATION

We have developed a methodology to solve the combined thermo-electric problem formulated in the preceding section using RadTherm. The approach is to use two meshes, one representing the two collector plates on which the voltage distribution is calculated, and a separate mesh representing the thermal behavior of the electrode/collector plate sandwich comprising a single cell. We employ a thermal analog to solve the electrical problem, wherein the 'temperature' output in the electrical part of the model is interpreted as voltage, and the 'heat flow' is interpreted as current. The electrical problem is illustrated conceptually in Figure 1, and the thermal problem is shown conceptually in Figure 2.

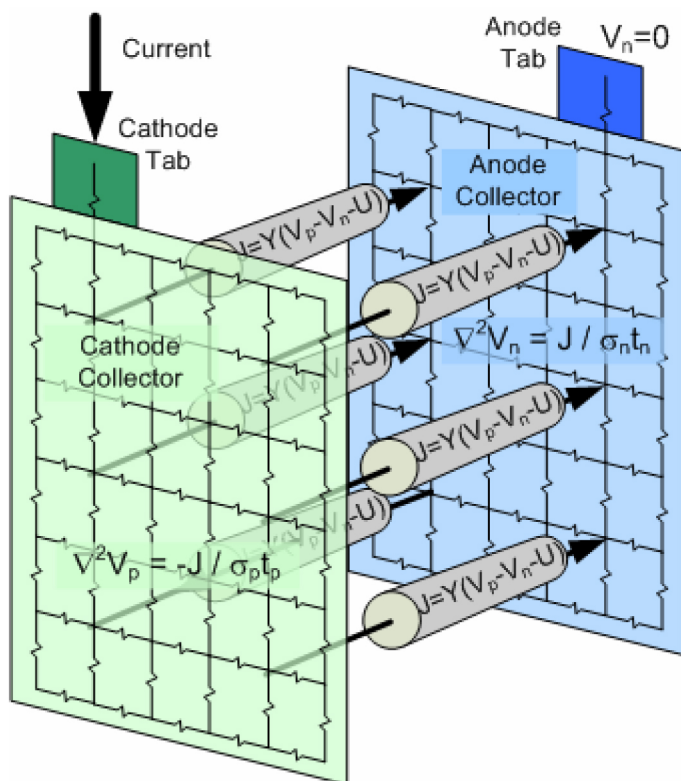


Figure 1. A conceptual representation of the electrical part of the model implemented in RadTherm.

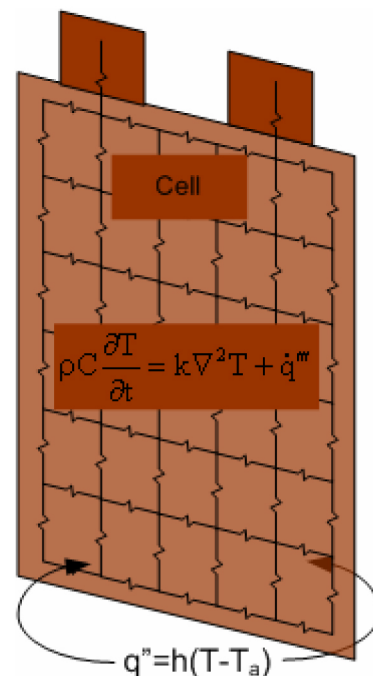


Figure 2. A conceptual representation of the thermal part of the model implemented in RadTherm.

In the electrical problem the voltage is constrained to be zero on the anode tab, and a net current is imposed on the cathode tab. A set of custom functions implemented as a plug-in module to RadTherm is employed to impose the proper local value of current density at each anode and cathode node. The current density is computed using equation (1), using the local nodal values of V_p and V_n obtained from the electrical solution.

Simultaneously, the nodal values of V_p and V_n are used to compute the local heating value from equations (7) and (8). This heat is imposed by the plug-in module on the appropriate nodes in the thermal part of the model. The thermal model also includes conventional thermal boundary conditions on the cell, i.e., convection and radiation from the face of the cell, with the possibility of adding conduction through the cell edges to cooled plates or fins.

The thermal model is transient. The electrical model is steady-state in the sense that there is no 'capacitance' in the electrical mesh, but transient current boundary conditions can be imposed on the model. The cell behavior also changes in response to the time-dependent computation of the local value of depth of discharge on the cell electrodes. During the solution, the plug-in module also adjusts the fitting parameters U and Y in response to changes in the ambient temperature being applied to the cell.

VALIDATION

Measurements on a lithium-ion cell were made to provide data for validation of the model. Terminal voltage and cell surface temperature were measured during constant current