

Thermal Analysis of a High-Power Lithium-Ion Battery System with Indirect Air Cooling

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ABSTRACT

Thermal behavior of a lithium-ion (Li-ion) battery module for hybrid electrical vehicle (HEV) applications is analyzed in this study. The module is stacked with 12 high-power pouch Li-ion battery cells. The cells are cooled indirectly with air through aluminum fins sandwiched between each two cells in the module, and each of the cooling fins has an extended cooling surface exposed in the cooling air flow channel. The cell temperatures are analyzed using a quasi-dimensional model under both the transient module load in a user-defined cycle for the battery system utilizations and an equivalent continuous load in the cycle. The cell thermal behavior is evaluated with the volume averaged cell temperature and the cell heat transfer is characterized with resistances for all thermal links in the heat transfer path from the cell to the cooling air. Simulations results are compared with measurements. Good agreement is observed between the simulated and measured cell temperatures. The results of this analysis demonstrate that the method developed in this study is reliable for characterizing thermal behavior of the Li-ion battery systems with similar structures and cooling methods.

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INTRODUCTION

A battery system or pack for hybrid electrical vehicle (HEV) applications usually consists of multiple modules connected in series to meet the required pack voltage. In each module, the cells are connected in a certain series-parallel combination to provide the required capacity and voltage. The performance, safety and life of a battery pack are influenced significantly by the working temperatures of the battery cells in the pack. As a result of high discharge/regen pulse currents, considerable heat can be generated in the battery cells, causing a rapid rise in the cell temperatures in a short operation period. The more heat accumulated in the cells, the higher the cell temperatures. The maximum cell temperature and maximum temperature difference in a cell are crucial factors to the cell durability and safety. To achieve optimal performance for a given battery pack, the working temperatures for the cells in the pack should be controlled within a proper range and temperature distributions in the cells should be as uniform as possible.

Thermal management of a battery pack lies on good understanding of thermal behavior of the cells in the battery pack under various pack operation and cooling conditions. A module is a basic unit for the battery thermal management due to two reasons: (1) the electrical currents are same for all the modules generally; (2) the condition for heat transfer

between the cells and the cooling medium (air or liquid) can be specified only at the module level, at which the cooling medium flow rate, variations in the cooling medium temperature, and heat transfer coefficients (HTC) on the cooling surfaces can be well characterized. A good battery thermal performance starts with a proper selection of cells and a good design of the modules electrically and thermally. Thermal modeling of the cells and modules can play an important role in the early stage of the pack development to ensure its durability and safety under specified pack duties. In following sections of this paper, an analysis will be reported on thermal behavior of a battery system with indirect air cooling under a thermal load condition simulating that in HEV applications.

BATTERY SYSTEM DESCRIPTION

The HEV battery pack under study has a 96S1P configuration, where S and P indicate the cells arranged in series and parallel. The pack has eight modules, each of which is stacked with twelve 8Ah high-power pouch Li-ion battery cells. The specifications of the cells are given in [Table 1](#). Due to being connected in series electrically, the thermal loads are same for all the modules under a given pack electrical load. If the pack cooling air flow is assumed to be equally distributed in all modules, then the modules in the

pack are thermally symmetric. Thus, only a representative module needs to be studied. The module structure is illustrated in Figure 1. The cells in the module are cooled indirectly with ambient air through six 2-mm thick aluminum cooling fins (or cooling plates) sandwiched between each two cells. Each of the cooling fins has an extended cooling surface exposed in the cooling air flow channel. The length for the module frame section is 10 mm and the length for the cooling fins exposed in the air flow channel is 23 mm. For the space between each pair of cells without a cooling fin, a 1-mm thick elastomeric thermal pad is inserted. Figure 2 shows the layout of a battery cell with its cooling fin and thermal pad. Here the multiple-battery-layer cell structure is simplified to containing only two equivalent electrodes for illustration of the cell cooling method. Each pair of cells with the shared cooling fin forms a basic cooling unit in the module. The 12-cell module has total of six cooling units. The cell temperatures can be controlled by changing the air inlet temperature and/or HTC on the cooling fins by regulating the cooling air flow.

Table 1. Cell specifications.

Cell chemistry	Lithium manganese oxide (LMO)
Nominal capacity	8 Ah
Nominal voltage	3.75 V
Internal resistance	< 1.5 mΩ
Operation temperatures	-25 to 60 °C
Mass	300 grams
Thickness × Width × Height	6 mm × 128 mm × 240 mm

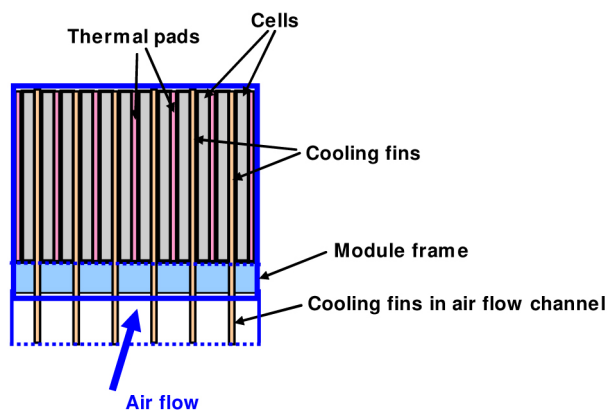


Figure 1. Illustration of a battery module with indirect air cooling.

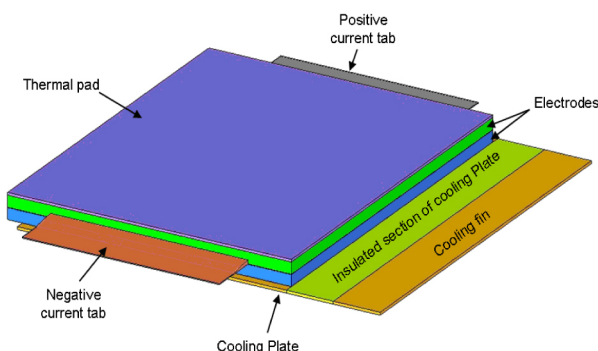


Figure 2. Illustration of cell cooling with a cooling plate for indirect air cooling.

BATTERY CELL PERFORMANCE CHARACTERIZATION

The battery thermal load is resulted from heat generations in the cells under an electrical load of the battery system. The heat generation in a cell is equivalent to the cell chemical energy dissipation during the cell usage. Dissipation in the cell chemical energy is reflected by the cell voltage drop, which characterizes various resistances in the electrochemical system in the cell under a given cell current. To understand the heat generation in the cell, it is necessary to first review the resistances rising during the cell usage.

A pouch Li-ion cell contains multiple parallel thin battery layers whose dimensions are on the order of 10^2 microns [1,2]. Each of these thin battery layers consists of two electrodes (anode and cathode), a separator and two current collectors (copper for the anode and aluminum for the cathode). The electrodes and the separator are all porous media with the pores filled with the electrolyte, as illustrated in Figure 3. During the cell usage, the current flow from one electrode to the other involves electronic charge transfer through an external electrical circuit and ionic charge transfer through the internal path, i.e., the electrolyte [3]. The current flows through the external electrical circuit and the electrolyte may be termed as the electronic current the ionic current respectively.

The charge or discharge performance of a battery cell is governed by the electro-thermal characteristic of the cell. The open circuit voltage (OCV) of the cell represents the best voltage that the cell can provide at given cell state of charge (SOC) and temperature T , i.e., $OCV = OCV(SOC, T)$. The cell performance is also influenced by the parameters related to the cell usage: the cell current and the cell internal resistance. For a cell under a discharge process with a current I , the dissipation of chemical energy in the cell can be characterized by the difference between OCV and the terminal voltage V as

$$V = E_0 - (\Delta V_1 + \Delta V_2 + \Delta V_3)$$

where $E_0 = \text{OCV}$, and ΔV_1 , ΔV_2 and ΔV_3 represent the three major losses due respectively to: (1) the ohmic resistance of the electrodes and current collectors, (2) the activation polarization at the electrode-electrolyte interfaces, and (3) the concentration polarization as a result of the unbalanced transient electronic current in the electrodes and ionic current in the electrolyte [2]. ΔV_1 is related to the electronic current and ΔV_2 and ΔV_3 are due largely to the ionic current resistances in the electrolyte. Figure 4 illustrates the E_0 - V relationship at different cell currents with fixed SOC and T (thus, $\text{OCV} = \text{constant}$). All three voltage losses increase with increasing the cell current.

As was first recognized by Randles [4], voltage drops due to resistances to the ionic current in an electrochemical system can be modeled electrically with a so-called Randles element that has an equivalent resistor and a capacitor linked in parallel. In the Randles element, the capacitor characterizes the activation polarization at the electrode-electrolyte interface (i.e., the electrochemical double layer capacitance [5]); the equivalent resistor has an electrical resistor and a so-called Warburg element (W) linked in series, characterizing respectively resistances due to charge transfer and diffusion of the electroactive particles in the electrolyte [4, 5, 6, 7]. Buller [8] and several other investigators [e.g., 7,9] pointed out that the Randles element may be approximated with two resistor-capacitor (RC) links in an equivalent electrical circuit for Li-ion battery cells. Thus, Eq.(1) may be expressed with an equivalent electrical circuit with the activation polarization and concentration polarization in the cell characterized by two RC links in the circuit as shown in Figure 5.

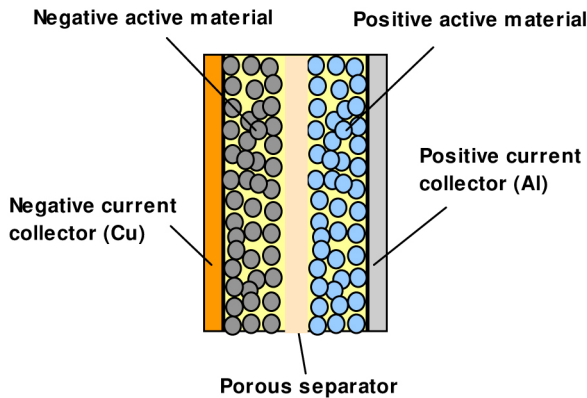


Figure 3. Illustration of the structure for a single battery layer in a pouch Li-ion cell.

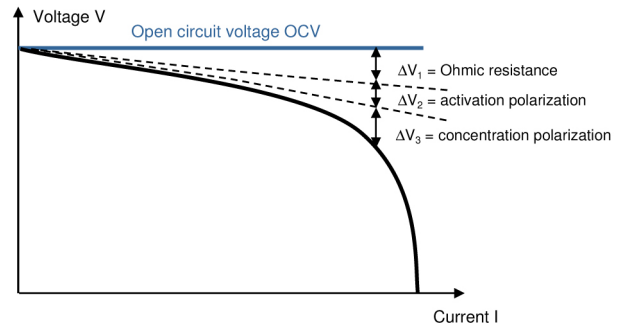


Figure 4. Illustration of voltage losses due to various resistances under different cell currents.

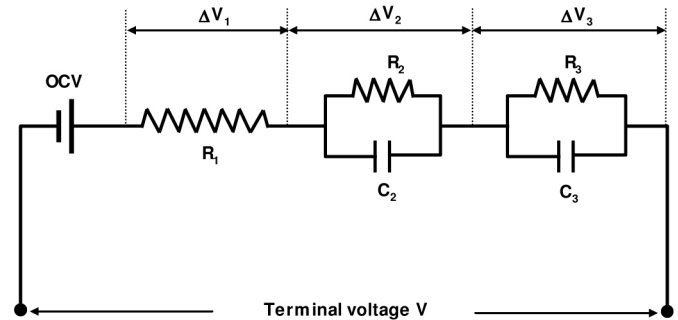


Figure 5. Equivalent electrical circuit for illustrating voltage losses due to various resistances.

Based on natures of different physicochemical processes in the battery cell and the components in the equivalent electrical circuit shown in Figure 5, Eq.(1) may be expressed alternatively as

$$V = \sum_0^n K_j(\text{SOC}) \times X_j(I, T) \quad (2a)$$

where K_j s are parameters varying with the electrothermal state and usage of the cell and X_j s are cell-chemistry-related functions characterizing the cell voltage such as the open circuit voltage, internal resistance, etc. Treating K_j s as parameters is on the ground that the time for the cell to reach a thermal equilibrium is much shorter than a chemical equilibrium because the ion migration and diffusion in the electrolyte from one electrode to the other are much slower processes than that of heat transfer in the cell [3]. Equation (2a) may be considered as a generic model for Li-ion batteries and it may be expressed in a vector form as

$$\begin{bmatrix} V_1 \\ \vdots \\ V_m \end{bmatrix} = \begin{bmatrix} K_0(\text{SOC}) & \dots & K_n(\text{SOC}) \\ \vdots & \ddots & \vdots \\ K_0(\text{SOC}) & \dots & K_n(\text{SOC}) \end{bmatrix} \begin{bmatrix} X_0(I_1, T) \\ \vdots \\ X_n(I_m, T) \end{bmatrix} \quad (2b)$$