

Thermal Characterization of a Li-ion Battery Module Cooled through Aluminum Heat-Sink Plates

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Ho Teng, Yue Ma, Kim Yeow and Marina Thelliez
AVL Powertrain Engineering Inc.

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ABSTRACT

The temperature distribution is studied theoretically in a battery module stacked with 12 high-power Li-ion pouch cells. The module is cooled indirectly with ambient air through aluminum heat-sink plates or cooling plates sandwiched between each pair of cells in the module. Each of the cooling plates has an extended cooling fin exposed in the cooling air channel. The cell temperatures can be controlled by changing the air temperature and/or the heat transfer coefficient on the cooling fin surfaces by regulating the air flow rate. It is found that due to the high thermal conductivity and thermal diffusivity of the cooling plates, heat transfer of the cooling plate governs the cell temperature distribution by spreading the cell heat over the entire cell surface. Influence of thermal from the cooling fins is also simulated. It is observed that cell temperature gradients are strongly influenced by the heat transfer resistance of the cooling plate and changes in the cooling air temperature shift the cell temperatures up or down without impacting the cell temperature distribution. It is shown in this study that indirect air cooling has a lower differential cell temperature and a more uniform cell temperature distribution in comparison to those in direct air cooling.

INTRODUCTION

Lithium-ion (Li-ion) batteries are becoming widely used rechargeable energy storage systems for hybrid electrical vehicles (HEVs) and electric vehicles (EVs). The performance and life of Li-ion batteries are influenced significantly by their working temperatures. Ideal working temperatures for Li-ion batteries fall in a narrow range from 20 °C to 40 °C. For HEV batteries, considerable heat can be generated in the cells as a result of high discharge/regen pulse currents, causing a rapid rise in the cell temperature in a short

operation period. The more heat accumulated in the cells, the higher their temperatures will be. 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, working temperatures of the cells in the pack should be controlled within a proper range and temperature distributions in the cells should be as uniform as possible.

A battery pack 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. Good battery thermal performance starts with a proper selection of cells and a good design of the modules from both electrical and thermal standpoint. A module is a basic unit for the battery thermal management because the condition for heat transfer between the cells and the cooling medium generally 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) at the cooling surfaces can be well characterized. Good thermal management of a battery pack lies on good understanding of thermal behavior of the cells in the pack under various pack operation and cooling conditions. 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 this paper, a theoretical investigation will be reported on thermal behavior of a battery module stacked with Li-ion pouch cells under operation conditions simulating HEV applications. The results of this investigation may provide guidance to a better design of the battery modules with similar structures.

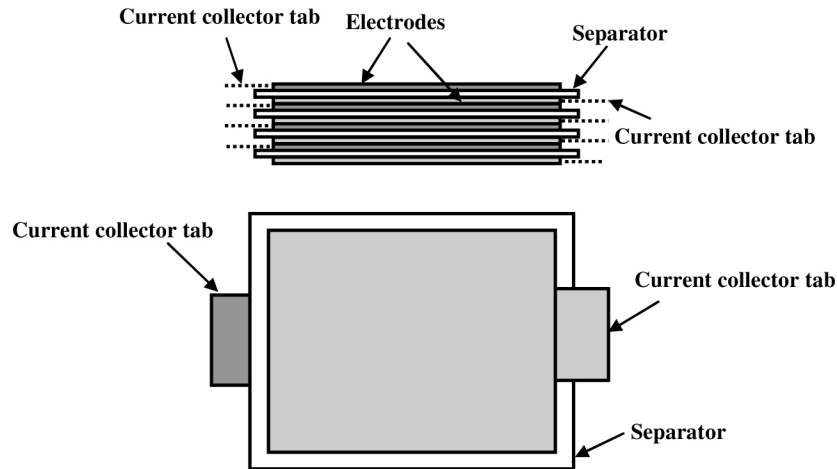


Figure 1. Illustration of the layered structure for a pouch Li-ion cell.

HEAT TRANSFER MODEL FOR CELL

Energy balance in an electrochemical system has been discussed in details by Bernardi et al. [1], Newman and Thomas-Alyea [2] and Thomas et al. [3]. Based on the theories developed in these previous studies, the rate of heat generation in a Li-ion cell q can be given as

$$q = \sum_j I_j \times (U_j^{av} - T \frac{\partial U_j^{av}}{\partial T}) - I \times V + R_{es} \quad (1)$$

where I_j is the volumetric current density resulting from the half reaction in the electrode j , U_j^{av} is the corresponding open circuit potential evaluated with the average composition, T is the local cell temperature, I is the total volumetric current density, V is the cell terminal voltage, and R_{es} represents the rest of the terms accounting for contributions from changes in the enthalpies due to mixing and phase change. For Li-ion cells, the heat generation from the enthalpies of mixing and phase change may be neglected in comparison to the other terms.

As illustrated in Figure 1, a pouch Li-ion cell is structured with multiple thin battery layers (with dimensions on the order of 10^2 microns) arranged in parallel in the cell. The positive and negative terminals or tabs of the cell can be designed on the same end or opposite ends. The cell thickness, typically <10 mm for high-power cells, is much less than the cell width and height. The temperature gradient across the cell thickness is generally small and negligible in comparison to those in the other two dimensions. In a heat-transfer analysis, the battery electrochemistry may be modeled with the overall reaction rather than with two half reactions in the positive and negative electrodes. Then Eq.(1) reduces to

$$q = I \times (U - V) - I \times \left(T \frac{\partial U}{\partial T} \right) \quad (2)$$

where U is the open-circuit cell voltage determined by the difference in the open circuit potentials at the positive and negative electrodes. Equation (2) may be expressed alternatively in the internal resistance R_i as

$$q = I^2 \times R_i - I \times \left(T \frac{\partial U}{\partial T} \right) \quad (3)$$

In Eq.(3), the first term is the heat generation due to the internal (irreversible) resistance and the second term is known as the reversible heat resulting from changes in the open circuit potentials with respect to the temperature at the two electrodes. The irreversible heat dominates the heat generation in a cell. In this study, the reversible heat is assumed to be negligible in comparison to the irreversible heat.

For a given cell, the current density can be determined based on the cell capacity, geometry, electrical load, and the state of charge (SOC). The cell internal resistance varies with the cell chemistry, SOC, temperature, design and the manufacturing process. For a given cell, the internal resistance is only a function of the cell temperature and the depth of discharge (DOD = 1 - SOC). Figure 2 shows dependence of the internal resistance on the temperature and DOD for a Li-ion cell. The cell internal resistance can be characterized with various methods [4]. If measured values of the internal resistance for a cell under investigation are not available, the bulk internal resistance of the cell may be estimated from the slopes of the voltage-current curves under a given temperature. The voltage-current characteristics can be obtained from the data for cell performance under different temperatures provided by the cell manufacturer. In Eq.(3),

both the current density and the internal resistance are local properties; hence, the overall current, voltage potential, bulk internal resistance and bulk SOC or DOD must all be localized in the initial characterization of the electrical field in the cell. The localized current density, voltage potential and electrical resistance are interrelated through the Ohm's law [3]. In an electro-thermal analysis of the cell, the characterization of the electrical field is updated continuously in a specified discharge or charge process.

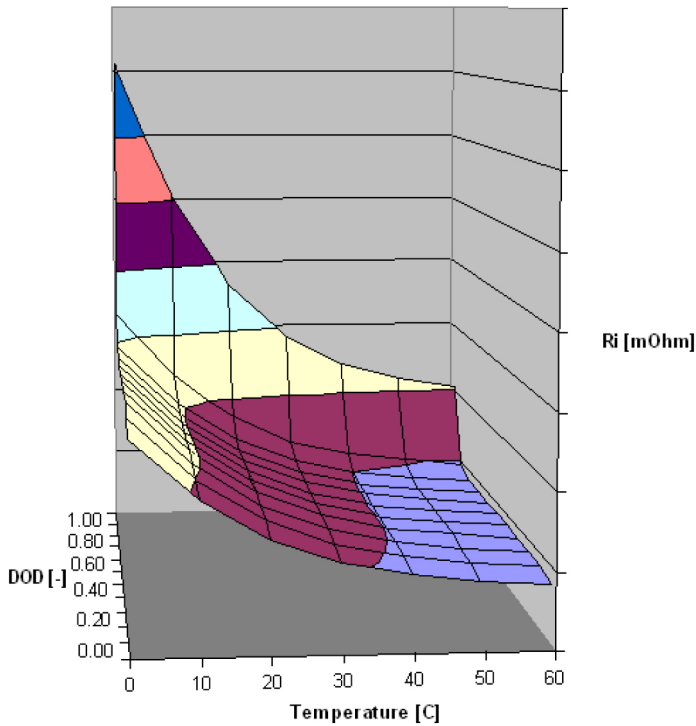


Figure 2. Internal resistance of a Li-ion cell with temperature and depth of discharge (DOD).

Figure 3 illustrates the structure of a single Li-ion cell. Each of the battery layers in a Li-ion cell 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 porous media with the pores filled with the electrolyte. Due to the fact that the temperature gradients across multiple battery layers along the cell thickness are small for a pouch cell, it is neither necessary nor practical to model the detailed structure of the cell in a heat-transfer analysis. Instead, the cell may be simplified and modeled as an equivalent heterogeneous solid medium, in which heat conduction takes place.

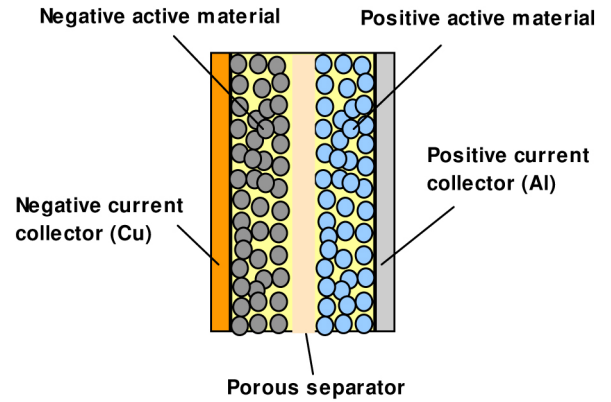


Figure 3. Illustration of the structure of a Li-ion battery layer.

Changes in the cell temperature due to the cell discharge or charge activities thus can be characterized with energy balance on a unit cell volume as

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q \quad (4)$$

where ρ , C_p and k are the local density, heat capacity and thermal conductivity of the cell medium and t is the time. Because of the layered structure, thermal behavior of the cell should be characterized with the effective thermal properties. Each of the battery layers with same thermal properties may be treated as a component of the heterogeneous solid medium. The composite local volumetric heat capacity may be expressed as

$$\rho C_p = \frac{\sum_i \rho_i C_{p,i} V_i}{\sum_i V_i} \quad (5)$$

where the subscript i indicates the properties for the component i . Thermal conductivities at the component interfaces should be determined based on connections of the components. For series connections, the composite thermal conductivity is given as

$$k = \frac{\sum_i L_i}{\sum_i (L_i / k_i)} \quad (6)$$

For parallel connections, the expression for the composite thermal conductivity becomes

$$k = \frac{\sum_i L_i k_i}{\sum_i L_i} \quad (7)$$

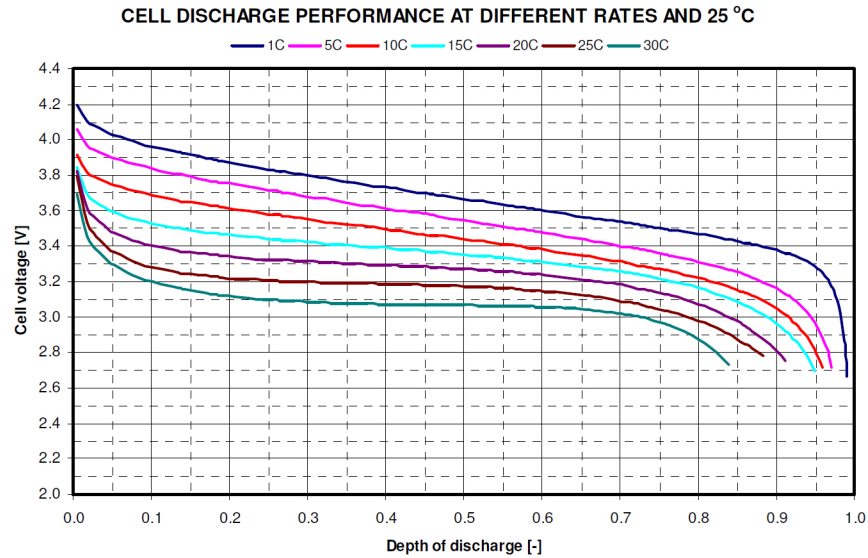


Figure 4. Cell discharge performance at room temperature.

In Eqs. (6) and (7), L_i and k_i are the thickness and the thermal conductivity for the component i respectively. Similarly, the composite electrical conductivities can also be expressed by Eqs. (6) and (7) in characterizing the electrical field of the cell.

THERMAL CHARACTERIZATION OF BATTERY MODULE

BATTERY MODULE DESCRIPTION

The battery module under study is stacked with 12 high-power Li-ion pouch cells. The specifications of the cell are given in Table 1. The cell discharge performance at room temperature is shown in Figure 4. All the cells in the module are connected in series, giving 8 Ah and 43.2 V for the module capacity and voltage. The cells in the module are cooled indirectly with ambient air through six 1-mm thick aluminum cooling plates sandwiched between each pair of cells. Each of the cooling plates has an extended cooling fin exposed in the cooling air flow channel. For the space between each pair of cells without a cooling plate, a 1-mm thick elastomeric thermal pad is inserted. Each pair of the cells with the sandwiched cooling plate is a basic cooling unit in the module. The cell temperatures can be controlled by changing the air inlet temperature and/or HTC at the cooling fins of the cooling plates by regulating the cooling air flow.

Table 1. Cell specifications.

Nominal capacity	8 Ah
Nominal voltage	3.6 V
Internal resistance	< 1.5 mΩ
Max discharge rate (≤ 30 sec)	25C
Operation temperatures	-25 to 50 °C
Mass	290 grams
Thickness $\times$ Width $\times$ Height	8.5 mm $\times$ 140 mm $\times$ 190 mm

FINITE ELEMENT MODELS FOR CELL AND MODULE

The finite element method (FEM) was originally developed for analyses of mechanical systems with complex structures. In recent years, many FEM tools have been extended to include analyses of complicated systems involving multi-physics. In this study, the electro-thermal behavior of the cells and the module will be characterized using the FEM tool ABAQUS [5].

In cases where the focus is on the cell thermal behavior and the detailed electrical field of the cell is not of interest, a simplified FEA model may be used. Several strategies for simplification of the electrical field of the cells can be found in the literature [6,7,8,9]. Considering that the temperature gradient across the thickness of a pouch cell is small, the cell may be further simplified to consist of only a single battery layer. Figure 5 shows a simplified FEA model for a representative cell in the module. The corresponding FEA model for the module is given in Figure 6. For a better view of the cooling units in the module, the frame of the module and electrical connectors are not shown in Figure 6. In this study, the module frame is assumed to be plastic, heat transfer through which is negligible.