

Electro-Thermal Modeling of a Lithium-ion Battery System

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ABSTRACT

Lithium-Ion (Li-ion) batteries are becoming widely used high-energy sources and a replacement of the Nickel Metal Hydride batteries in electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). Because of their light weight and high energy density, Li-ion cells can significantly reduce the weight and volume of the battery packs for EVs, HEVs and PHEVs. Some materials in the Li-ion cells have low thermal stabilities and they may become thermally unstable when their working temperature becomes higher than the upper limit of allowed operating temperature range. Thus, the cell working temperature has a significant impact on the life of Li-ion batteries. A proper control of the cell working temperature is crucial to the safety of the battery system and improving the battery life. This paper outlines an approach for the thermal analysis of Li-ion battery cells and modules. The thermal behavior was analyzed of a commercially available A123 Hymotion™ L5 PCM pack assembled with the A123-26650 Li-ion cylindrical cells using the electrothermal finite element model developed in this paper. The simulation results showed good agreement with measurements. This demonstrates that the electro-thermal finite element model developed in this study can reasonably characterize the thermal behavior of a battery pack. Although only cylindrical cells are analyzed, the method for characterizing the thermal behavior of the Li-ion battery cells developed in this study can also be applied to battery cells with other geometries, such as prismatic and pouch cells.

INTRODUCTION

Because of their high cell voltage and energy density, the secondary lithium ion (Li-ion) batteries are promising power sources for electric vehicles (EVs), hybrid electric vehicles (HEVs) and the plug-in hybrid electric vehicles (PHEVs).

Because some materials in the Li-ion cells have low thermal stabilities and they may become thermally unstable when their working temperature becomes higher than the upper limit of allowed operating temperature range, the thermal management of the battery system is crucial to both the safety of the battery system and improving the battery life. For vehicle propulsion applications the reliability of the battery system must be high and the battery pack should allow for 10 to 15 years of the operation. The maximum cell temperature and the maximum temperature difference in a battery cell are crucial factors to the battery durability and safety. In automotive applications, it is required that the battery packs have sufficient capacity and withstand transient high power utilizations, which often generates large heat as well as high temperature difference in the battery cells. Most Li-ion battery suppliers require that the working temperatures for their products be controlled within a proper temperature range and the cell temperature should be as uniform as possible to achieve optimal battery performance and avoid battery system failure.

A battery pack usually consists of many cells that are connected in series or parallel to meet the required capacity and voltage for the pack. The complexity of the battery pack increases the complexity of the battery thermal management. Good battery thermal performance starts with a proper selection of the battery cells and good design of the battery modules and the pack. The module hardware, such as cell connectors, is also critical to the battery operation. The thermal modeling of the battery cell, the modules and the pack can play an important role in the development stage to ensure the durability and safety of the battery pack.

Although sophisticated electrochemical models are available for the battery cell performance simulation, they can not capture the heat transfer within the actual cell geometry or connection hardware of the battery system. Bharathan and

Pesaran [1] proposed a 3D finite element based electro-thermal modeling process for improving the battery design. However, their model does not capture the transient nature of the internal resistance of the battery cells during charge or discharge activities. Inui et al. [2] developed a 3D simulation code for the transient response of the temperature distribution in the Li-ion secondary batteries during a discharge process. Their model cannot capture the heat generation from the electrical current flowing through the current collecting tabs of the battery cells.

Considering the advantages and disadvantages of the models aforementioned, the present authors developed a 3D simulation approach for the transient response of the temperature distribution in the Li-ion batteries during a battery discharge/charge process. Because the cylindrical cells are widely used in commercially-available Li-ion battery packs, a battery pack assembled with the cylindrical Li-ion cells is selected for investigation. The details in the approach developed and the thermal analysis on a commercially available pack will be discussed in the rest sections of this paper.

BATTERY SYSTEM DESCRIPTION

The battery system under consideration is an A123 Hymotion™ L5 PCM battery pack [3, 4]. This pack is selected for investigation because it has been proposed for PHEV applications [3] and thus it should have the characteristics for both the HEV and EV battery packs. The pack contains seven modules with each having two half modules sharing a same circuit board. Each of the 14 half modules is assembled with 44 high-power A123 26650 Li-ion cylindrical cells (model ANR26650M1A). The cell specifications are given in Table 1.

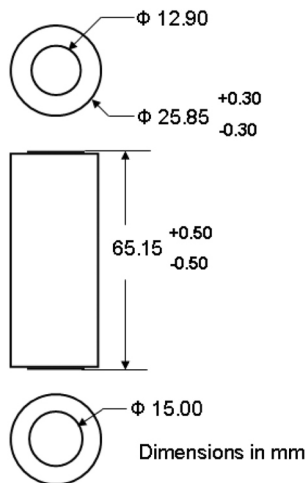


Figure 1. Dimensions of A123 26650 Li-ion cylindrical cell (model ANR26650M1A).

Table 1. Cell specifications of Li-ion cylindrical cell ANR26650M1A

Nominal capacity and voltage	2.3Ah, 3.3V
Internal impedance (1kHz AC)	8mΩ typical
Internal resistance (10A, 1s DC)	10mΩ typical
Recommended standard charge method	3A to 3.6V CCCV, 45 min
Recommended fast charge method	10A to 3.6V CCCV, 15 min
Maximum continuous discharge	70A
Pulse discharge at 10 sec	120A
Cycle life at 10C discharge, 100% DOD	Over 1000 cycles
Recommended pulse charge/discharge cutoff	3.8V to 1.6V
Operating temperature range	(-)30°C to (+)60°C
Storage temperature range	(-)50°C to (+)60°C
Core cell weight	70 grams

The 44 cells in a half module are connected in 11P4S, giving 25.3 Ah (= 11×2.3 Ah) and 13.2 V (= 4×3.3 V) for the half module or 25.3 Ah and 26.4 V for a full module. Because all the 14 half modules are connected in series, the A123 Hymotion™ L5 PCM pack has a nominal capacity 25.3 Ah and a nominal voltage 184.8 V. Figure 2 shows the pack with an exploded view and the cell packing in a half module. The cooling air flows into all the half modules in parallel through a common inlet chamber. The minimum module air flows (i.e., for two half modules) at different air inlet temperatures for discharge rates ≤ 3C suggested by A123 [5] are presented in Figure 3. Also presented in Figure 3 are the allowed air inlet temperatures vs. air flows, which were predicted by the authors of this paper from a model developed based on the minimum module air flow and the air flow vs. inlet temperature relationship for discharge rates ≤ 3C provided by A123 [5]. The minimum module air flows for discharge rates > 3C represent the extrapolation.

Although Figure 3 is good guidance for the module cooling design, it does not provide the information on the cell temperature distribution in a module and how the cell connections or bus bars affect the cell temperatures. The information on the cell temperature can only be obtained with a detailed thermal analysis on the cell and the module. In the following sections, the detailed thermal analyses on the A123-26650 cells and module will be discussed.

THERMAL ANALYSIS OF THE BATTERY MODULE

Because all the half modules are thermally symmetric in the A123 Hymotion™ L5 PCM pack, if the air flow may be

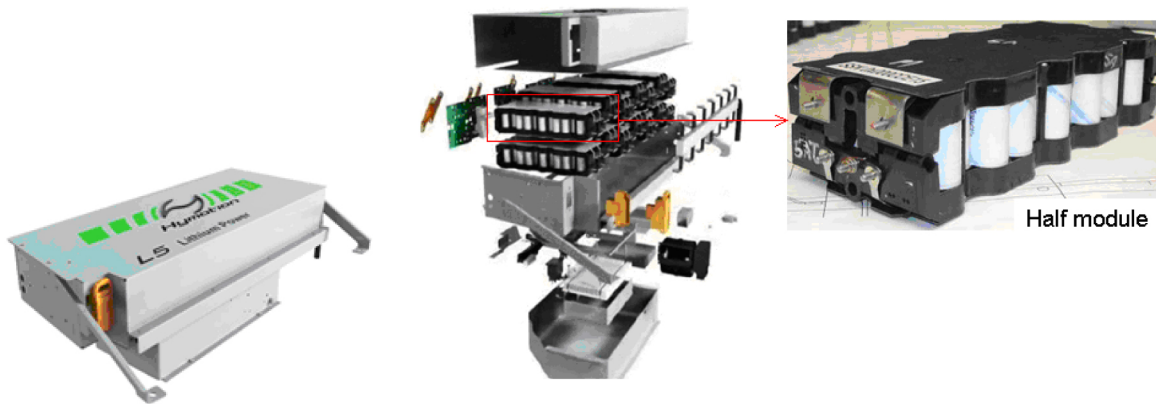


Figure 2. Exploded view of A123 Hymotion™ L5 PCM battery pack and a half module.

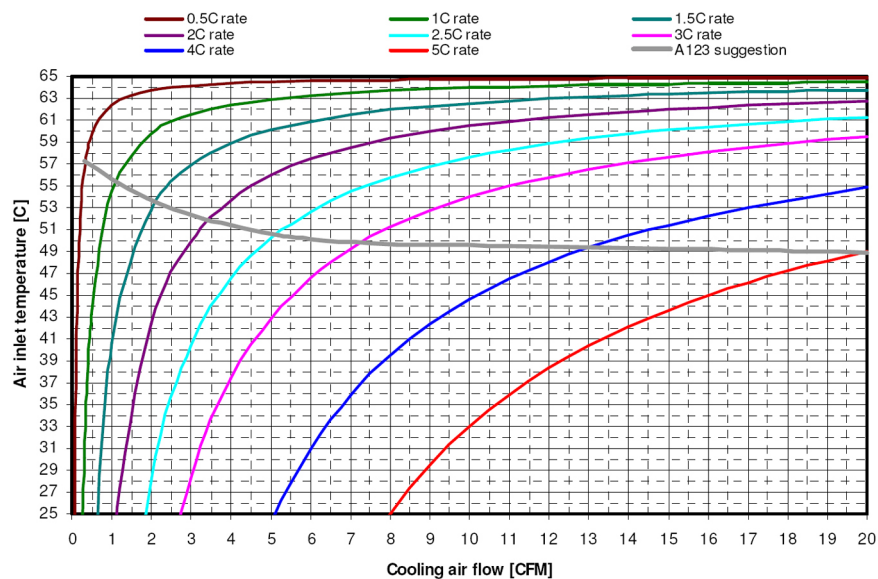


Figure 3. Minimum module air flow vs. air inlet temperature and discharge rate.

assumed to be uniform in the air inlet chamber of the pack, only a single half module needs to be studied for characterizing the thermal behavior of the pack. In this study, the thermal analysis will be conducted at two levels: a cell level analysis which investigates the minimum required heat transfer coefficient (HTC) to limit the maximum cell temperature below the maximum allowed working temperature specified by the cell manufacturer; a module level analysis which simulates the air flow that can provide the required HTC by the cells and the cell temperature distribution in the module.

THERMAL ANALYSIS OF THE BATTERY CELL

Finite-Element Model for the Battery Cell

Figure 4 shows a typical structure for a Li-ion cylindrical battery cell [6]. The core of the cell is a spirally-wound

design. This design is widely used because the cell can be assembled by an automatic process. The larger the cell capacity is, the more winds in the spiral will be. Each wind in the core is an anode-separator-cathode combination with two current collectors (positive and negative) associated with it. The anode, the separator and the cathode have porous structures with the pores filled with the electrolyte.

Although the finite element method (FEM) was originally developed for numerical analyses of mechanical systems with complex structures, it has found more and more applications in non-mechanical analyses. In this study, it will be used to characterize the electro-thermal behavior of the battery cells and the module.

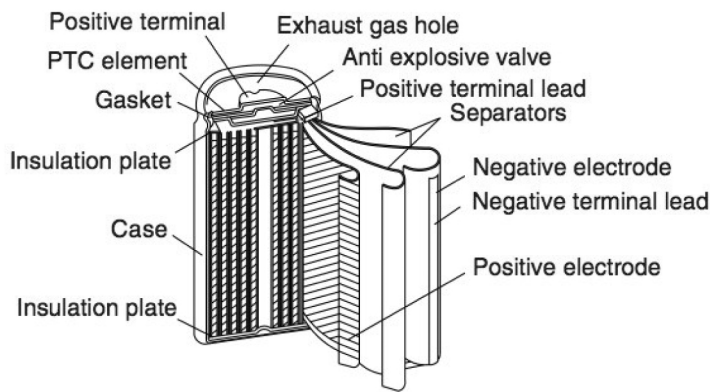


Figure 4. Illustration of the inside structure of a cylindrical Li-ion cell.

The non-homogeneous and anisotropic structure of the roll, the extreme thickness of each layer and the complicated interfaces between different materials make the thermal modeling of a battery cell very complex. In order to obtain an accurate thermal analysis of a battery cell, the cell geometry and configuration, as well as the physical, chemical and electrochemical properties of the cell materials should be delineated as accurately as possible in the model. A detailed 3D finite element model, which may precisely describe the exact configuration of the roll and properly handle the material interfaces, would have millions of grid points and thus it would require a powerful computer and a tremendous calculation time to obtain desired results. Such a complicated model may not be practical nor acceptable in the engineering practice. It is common and critical to adopt some simplified strategies in developing battery models. Several simplification strategies have been reported in the literatures. Inui et al. [2] and Al-Hallaj et al. [7] modeled a cylindrical battery cell as a thermally homogeneous medium with effective thermal physical properties. Hatchard et al. [8] used a series of concentric rings to depict the configuration of a spiral wound cell. Evans and White [9] suggested that the spiral of the cell may be modeled using the connected semicircles. All these proposed methods have their advantages and disadvantages.

The internal resistance of a battery cell is proportional to the loss in the electrical energy and heat generation in the cell. The lack of current carrying paths between the active materials of the anode and cathode and the external terminals of the cell is a big contributor to the cell internal resistance. High capacity cells have larger electrodes, for which the current collection design can be more challenging. Multiple tabs must be used for spirally wound cells. In high power battery cells each of the two electrodes can have 4 ~ 12 tabs. Having more tabs is a way to minimize the cell internal resistance. These tabs may be positioned with equal intervals in length along each of the two electrodes as discussed in [13]. For example, for an electrode with four tabs, the tabs

should be positioned as close as possible to 1/8th, 3/8th, 5/8th, and 7/8th of the electrode length. Such an arrangement of the tabs can minimize the distance for the current to travel from the electrode to the current collector tabs and the battery terminals. The battery internal resistance decreases with reducing the current travel distance within the electrode. Figure 5 illustrates tab positions and current flow in a wound battery cell with four current collection tabs. In Figure 5, the left part shows the rolled electrode from the rolled edge and the right part shows a plan view of an unrolled electrode with the four tabs positioned at 1/8th, 3/8th, 5/8th, and 7/8th of the electrode length. With the tabs positioned in Figure 5, the current flows more evenly in the electrode and the local current flow is associated largely with the nearest tab. This suggests that the current flow in a 4-tab electrode be equivalent to those in four single-tab electrodes in parallel. On this ground, the wound spiral core may be modeled with four concentric sub-regions. Each sub-region is a basic battery element with two electrodes, one separator and two current collecting tabs. These sub-regions are thermally connected. Figure 6 shows a schematic structure for a wound spiral.

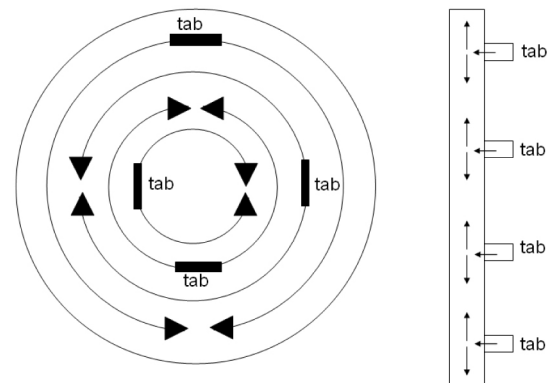


Figure 5. Schematic view of current collecting tabs and current flow in a wound battery cell.

A finite element model was developed for the A123-26650 Li-ion cylindrical cell under study using the FEM tool ABAQUS [10]. In the model, the spiral wound roll of the cell is modeled with a series of concentric rings and each ring is a thermally homogeneous medium with one set of effective thermal physical properties. To minimize the size of the finite element model, the cell structure is further simplified and the spiral region of the cell is modeled with only three concentric rings: the inner ring is an equivalent cathode with a positive current collector connecting it with the positive terminal of the cell; the outer ring is an equivalent anode with a negative current collector connecting it with the negative terminal of the cell; the middle ring represents the separator. Each of the three rings is assumed to be a homogeneous medium. This simplified finite element model is shown in Figure 7.