

Characterizing Thermal Runaway of Lithium-ion Cells in a Battery System Using Finite Element Analysis Approach

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ABSTRACT

In this study, thermal runaway of a 3-cell Li-ion battery module is analyzed using a 3D finite-element-analysis (FEA) method. The module is stacked with three 70Ah lithium-nickel-manganese-cobalt (NMC) pouch cells and indirectly cooled with a liquid-cooled cold plate. Thermal runaway of the module is assumed to be triggered by the instantaneous increase of the middle cell temperature due to an abusive condition. The self-heating rate for the runaway cell is modeled on the basis of Accelerating Rate Calorimetry (ARC) test data. Thermal runaway of the battery module is simulated with and without cooling from the cold plate; with the latter representing a failed cooling system. Simulation results reveal that a minimum of 165 °C for the middle cell is needed to trigger thermal runaway of the 3-cell module for cases with and without cold plate cooling. During thermal runaway, the cell heat propagates through all the available thermal paths, including the cooling plates that are in contact with the cold plate, the thermal pads that separate the battery cooling units, and the busbars that connect the terminal tabs of the cells. With the functioning cooling system, heat transfer to the neighboring cells is slower and thus it takes a longer time for these cells to runaway. However, the cold plate cooling could not prevent the thermal runaway of these cells because the cooling capacity of the cold plate is designed only for dissipating the cell ohmic heat during normal module operations. The simulation results demonstrate that the FEA model developed in this study can provide useful information on the cell thermal runaway, such as the onset of thermal runaway, maximum runaway temperature, and thermal propagation from the runaway cell to the neighboring cells. This information can be used to predict gas venting from the cell and to provide guidance in the design of safety features of a battery pack enclosure. The analysis approach developed in this study can also be used for cells with different chemistry if the ARC data are available.

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INTRODUCTION

Because of their high gravimetric energy and power densities, lithium ion (Li-ion) batteries are becoming the most promising energy storage devices for electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles. Li-ion battery cells can be made in different geometries (cylindrical, prismatic or pouch) [1,2], each of which has advantages and disadvantages in packaging and cooling. Pouch type cells are commonly used in large-capacity and high-power battery pack designs because of their high packing efficiency. A pouch Li-ion cell contains multiple parallel thin battery layers with thickness < 200 microns generally [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 electrolyte, as illustrated in [Figure 1](#). During 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 [2, 3, 4]. The current flows through the external electrical circuit and the electrolyte are typically referred to as electronic current and ionic current respectively.

Table 1 lists the five most commonly used Li-ion batteries [5]. For these Li-ion batteries, the anode material is carbon (soft or hard carbon) and the cathode materials are either lithium oxide (LCO, NCA, NMC, or LMO) or lithium phosphate (LFP) [5,6]. Some of the materials in these batteries have low thermal instabilities and they decompose if the battery temperatures become too high.

Table 1. Five leading chemistries for Li-ion batteries

Chemical name	Material	Abbreviation	Short form
Lithium cobalt oxide	LiCoO_2	LCO	Li-cobalt
Lithium manganese oxide	LiMn_2O_4	LMO	Li-manganese, or spinel
Lithium nickel manganese cobalt oxide	LiNiMnCoO_2	NMC	NMC
Lithium nickel cobalt aluminum oxide	LiNiCoAlO_2	NCA	NCA
Lithium iron phosphate	LiFePO_4	LFP	Li-phosphate

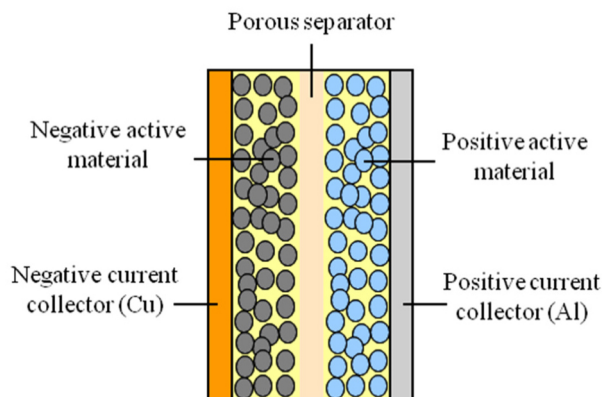
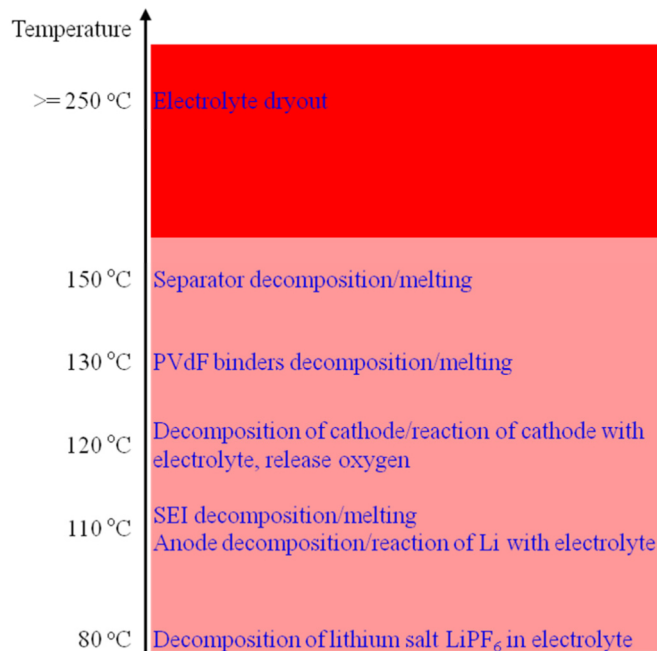
**Figure 1. Structure of a single battery layer in a pouch Li-ion cell.**

Figure 2 shows the thermal instabilities of the battery materials based on the material data reported in the literature [2,3]. In Figure 2, SEI is the solid electrolyte interface formed between the anode and the electrolyte, which prevents the chemical reactions between the anode and electrolyte. Thermal instabilities of the battery materials lead to exothermic decomposition reactions. For the oxide-based cathode, oxidation reactions can take place at the cathode when the cell temperatures become sufficiently high. The heat released from decomposition and oxidation reactions result in the cell self-heating. Because the heat generation rate due to the cell self-heating is several orders greater than that of the cell ohmic heat in normal cell operations, it is beyond the capability of the battery cooling system which is designed only for dissipating the cell ohmic heat. As a result, the cell thermal runaway takes place. Although thermal runaway of a battery cell may be triggered by electrical abuses, mechanical abuses or thermal abuses, the cause for thermal runaway of a Li-ion cell is the cell self-heating resulting from the chemical reactions due to thermal instabilities of the cell materials. For the five cathode chemistries listed in Table 1, the gravimetric specific heat release during thermal runaway can be given in descending order as: LCO > NCA > NMC > LMO > LFP [7, 8, 9]. LFP has the lowest heat release because it does not release oxygen during thermal runaway due to the strong olivine crystalline structure for LiFePO_4 [10].

**Figure 2. Thermal instabilities of some battery materials in Li-ion batteries.**

Although battery systems are always designed with thermal management systems for controlling the cell temperatures with high reliability for safe operation, in reality, failures or accidents are inevitable. Thus, the battery pack enclosure must be designed with safety features to deal with possible thermal runaway for some cells in the pack. This requires the information on the onset of the cell thermal runaway for a given cell chemistry, maximum runaway cell temperature, and thermal propagation from the runaway cell to the neighboring cells. This study investigates thermal runaway of the 70 Ah Li-ion cells triggered by over-heating (thermal abuse) of the middle cell in a 3-cell mini battery module using a 3D finite element analysis (FEA) approach. The detailed thermal runaway analysis and the characteristic parameters will be reported in the following sections.

BATTERY SYSTEM DESCRIPTION

The mini battery module under study is stacked with three 70Ah high-power NMC pouch cells whose specifications are given in Table 2. The cells in the module are cooled with liquid indirectly through a tubular type cold plate [11]. The FEA model for the module is shown in Figure 3. The module

consists of three basic cooling units (Figure 3a). As shown in the exploded view (Figure 3b), each cooling unit consists of a battery cell, a 1.5-mm thick aluminum cooling plate and an elastomeric thermal pad. The cell in each cooling unit is cooled via the aluminum cooling plate which is in contact with a liquid-cooled cold plate. The side surface of the cell not in contact with the cooling plate is thermally insulated from the adjacent cooling unit by the thermal pad. The three battery cells are connected in series electrically as shown in the sectional view (Figure 3c). Perfect thermal contacts are assumed for all the contact surfaces, i.e., between cell and cooling plate, cell and thermal pad, thermal pad and cooling plate, cooling plates and cold plate.

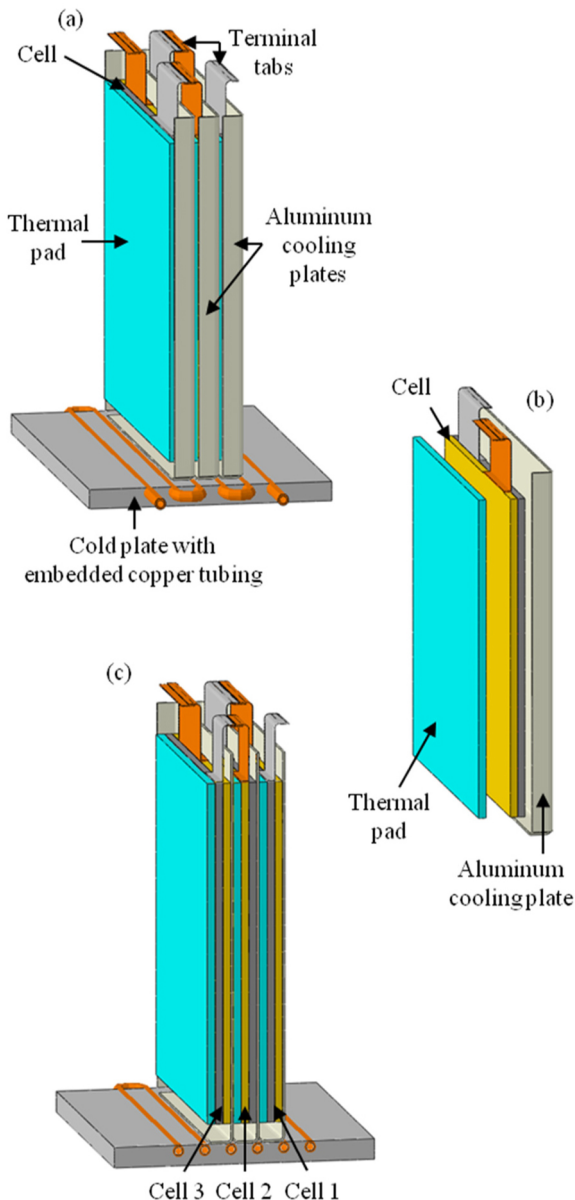


Figure 3. FEA model: a) 3-cell module, b) exploded view of a cooling unit, c) sectional view of the module.

Table 2. Cell Specifications.

Nominal capacity	70 Ah
Nominal voltage	3.7 V
Internal resistance	< 0.7 mΩ
Max discharge rate (<10 sec)	10C
Operation temperatures	-15 to 60 °C
Mass	1450 gram
Thickness x Width x Height	11 x 248 x 260 (mm)

CELL HEAT TRANSFER MODEL

As aforementioned, Li-ion cells are structured with multiple thin battery layers arranged in parallel in the cell. The layered cell structure is simplified with a continuous medium and the cell is modeled as an equivalent heterogeneous solid medium where heat conduction takes place. Figure 4 shows the equivalent single layer cell model. Techniques for the battery modeling in this study are the same as in the authors' previous SAE papers [12,13].

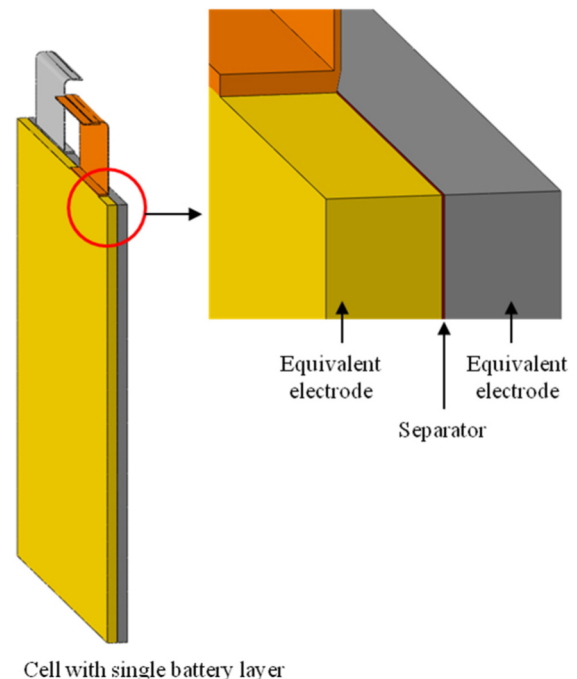


Figure 4. Battery cell characterized with single equivalent battery layer.

Changes in the cell temperatures due to the cell heat can be characterized with energy balance on a unit cell volume as

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q \quad (1)$$

where ρ , C_p and k are the local density, heat capacity and thermal conductivity of the cell medium; T is the temperature, t is the time, and q is the volumetric heat generation in a cell. Thermal properties involved in Eq. (1) should be