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Short communication

Simulation of abuse tolerance of lithium-ion battery packs

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Abstract

A simple approach for using accelerating rate calorimetry data to simulate the thermal abuse resistance of battery packs is described. The thermal abuse tolerance of battery packs is estimated based on the exothermic behavior of a single cell and an energy balance than accounts for radiative, conductive, and convective heat transfer modes of the pack. For the specific example of a notebook computer pack containing eight 18650-size cells, the effects of cell position, heat of reaction, and heat-transfer coefficient are explored. Thermal runaway of the pack is more likely to be induced by thermal runaway of a single cell when that cell is in good contact with other cells and is close to the pack wall.

Keywords: Lithium-ion battery; Thermal abuse; Battery pack; Accelerating rate calorimetry

1. Introduction

The safety of lithium-ion cells has been of foremost concern from their inception as evidenced by the number of safety devices developed specifically for lithium-ion cells [1,2]. However, much less attention, at least in the technical literature, has been paid to the safety of lithium-ion packs. For example, lithium-ion packs for portable computers represent a significant portion of the market for 18650-size cells, and only a few papers [3,4] address the thermal behavior, much less the abuse tolerance, of a typical pack. This short communication presents a new approach for estimating the thermal abuse tolerance of lithium-ion battery packs based on the behavior of individual cells.

2. Model

Approaches to modeling the thermal abuse of lithium-ion cells have been reviewed previously [5]. For pack modeling, the heat generated in the cell is determined experimentally and then used in an energy balance for the pack to predict the pack temperature. The heat generation rate of the cell can be obtained by experimental characterization using accelerating rate calorimetry (ARC); ARC is widely used to characterize lithium-ion cells [6–8] but a review is beyond the scope of this short communication. The ARC experiment provides direct measurement of the self-heating rate as a function of temperature. For simplicity, consider a hypothetical case where the ARC experiment for a single lithium-ion cell produces a normal curve (see Fig. 1). A more complex ARC profile produced from an actual experimental characterization of a cell could be considered, but an idealized situation is used here to help explain the method. The self-heating rate (SHR) is used to estimate the decomposition rate of the cell (R_d) by:

$$R_d\,[s^{-1}] = \frac{\mathrm{SHR}\,[K\,s^{-1}]}{T_{max}\,[K] - T_{min}\,[K]} \quad (1)$$

where T_{min} refers to the onset temperature for the thermal reaction and T_{max} to the temperature at which the reaction is complete (see Fig. 1). The decomposition rate can be used to estimate the heat generated from the cell (q_{gen}) by:

$$q_{gen}\,[W] = H_{rxn}\,[J] R_d\,[s^{-1}],$$
$$H_{rxn} = m_{cell}\,[g] c_{p,cell}\,[J\,g^{-1}\,K^{-1}]\,(T_{max} - T_{min}) \quad (2)$$

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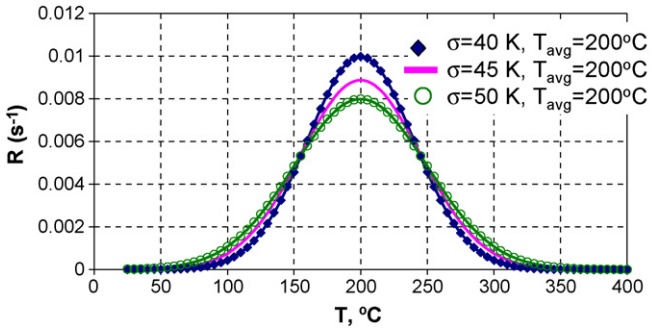

Fig. 1. Reaction rate as a function of temperature.

Each cell is taken to be at a single temperature; that is, temperature gradients within cells are not considered. This is a reasonable approximation for small cells like the 18650 size [9]. Using this heat generation term, an energy balance can be written for each cell in the pack:

$$
\begin{aligned}
m_i c_{p,i} \frac{\mathrm{d}T_i}{\mathrm{d}t} &= \sum_{k=1,6} q_{\mathrm{wall},k,i} + \sum_{k\neq i} q_{\mathrm{comp},k,i} + q_{\mathrm{air},i} + q_{\mathrm{gen},i} \\
q_{\mathrm{wall},k,i} &= \sigma\varepsilon_i A_{ik,\mathrm{rad}}(T_k^4 - T_i^4) + h_{ik} A_{ik,\mathrm{contact}}(T_k - T_i) \\
q_{\mathrm{comp},j,i} &= \sigma\varepsilon_i A_{ij,\mathrm{rad}}(T_j^4 - T_i^4) + h_{ij} A_{ij,\mathrm{contact}}(T_j - T_i) \\
q_{\mathrm{air},i} &= \sum_m h_{im} A_{i,\mathrm{air}}(T_m - T_i) \\
h_{im} &= \frac{k_i k_m}{L_i k_i + L_m k_m}
\end{aligned}
\qquad (3)
$$

where m_i is the mass of the cell, $c_{p,i}$ the heat capacity of the cell, σ the Stefan–Boltzman constant, ε the emissivity of the cell, $A_{ij,\mathrm{rad}}$ the area of component j that is visible to cell i, h_{ij} the heat-transfer coefficient as defined above, k_i the thermal conductivity of component i, and L_i is the distance from the center of mass to the surface of component i. A similar energy balance can be written for each wall that includes an additional term for heat-transfer from the wall to the external environment. The Battery Design Studio® software automatically computes the contact areas ($A_{ij,\mathrm{contact}}$) of the various pack components as well as the line-of-sight areas ($A_{ik,\mathrm{rad}}$) that are needed for the convective and radiative heat-transfer calculations, respectively [10]. The set of ordinary differential equations are solved using a Runge Kutta method.

To apply these energy balances, a pack layout must be defined. For example, consider the pack layout shown in Fig. 2 (based on the design presented by Maleki and Shamsuri [4]) with the thermal properties listed in Table 1.

Table 1
Thermal properties of pack

Component	Weight (g)	Heat capacity ($\mathrm{J\,g^{-1}\,K^{-1}}$)	Thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
Cell	43.8	0.67	n.a.
Circuit board	50.0	0.7	500.
Pack wall (x–z)	19.4	0.7	0.1
Pack wall (x–y)	2.7	0.7	0.1
Pack wall (y–z)	4.2	0.7	0.1

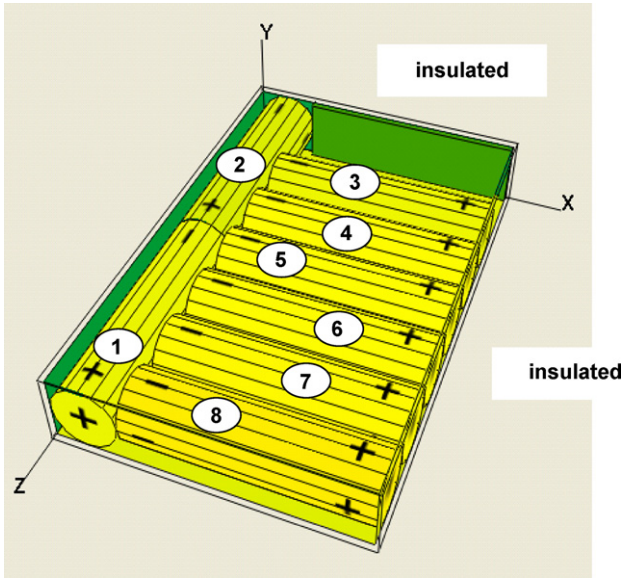

Fig. 2. Pack design with eight cells. Three walls are insulated (y–x plane at $z = 0$, x–z plane at $y = 0$, and y–z plane at $x = 85$ mm).

The pack consists of eight cells, labeled as shown in Fig. 2. Three of the walls of the pack are posited to be insulated and treated as adiabatic: the bottom (x–z plane), the right side (y–z plane), and the front (x–y plane). A small printed circuit board (PCB) is included in the pack, but spaced away from cell #3.

3. Simulation results and discussion

A common experimental method used to explore the abuse tolerance of a pack is to force one cell into thermal runaway and observe the resultant behavior: will other cells also go into thermal runaway or will the pack cool down? This can be an expensive test, so it is usually limited in scope. For example, only the cell in a single position might be brought into thermal runaway. However, with simulation, a wide number of experimental conditions can be explored. Here the effects of cell position (1–8), heat of reaction (corresponding to an adiabatic temperature rise of 270–330 K), and heat-transfer coefficient (10–100 $\mathrm{W\,m^{-2}\,K^{-1}}$) are explored.

To start the simulation, the cell in one position is set to a temperature that is high enough to induce thermal runaway (175 °C). Fig. 3 includes eight cases; each case shows the temperature profiles of each cell in the pack as a function of time for the case where the adiabatic temperature rise of a single cell is 240 K, the initial pack temperature is 25 °C except for the one cell which is at 175 °C, and the pack heat-transfer coefficient to the environment is 10 $\mathrm{W\,m^{-2}\,K^{-1}}$. In every case shown in Fig. 3, the pack does not go into thermal runaway, despite the low value of the heat-transfer coefficient; apparently the heat of reaction is too low to induce thermal runaway. If the pack is completely adiabatic, then all the cells go into thermal runaway and the pack reaches a steady-state temperature ~265 °C.

Fig. 4 shows the case where the adiabatic temperature rise of a single cell is 300 K and the heat-transfer coefficient is