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Effect of thermal contact resistances on fast charging of large format lithium ion batteries

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ABSTRACT

A two dimensional electrochemical thermal model is developed on the cross-plane of a laminate stack plate pouch lithium ion battery to study the thermal performance of large format batteries. The effect of thermal contact resistance is taken into consideration, and is found to greatly increase the maximum temperature and temperature gradient of the battery. The resulting large temperature gradient would induce in-cell non-uniformity of charging-discharging current and state of health. Simply increasing the cooling intensity is inadequate to reduce the maximum temperature and narrow down the temperature difference due to the poor cross-plane thermal conductivity. Pulse charging protocol does not help to mitigate the temperature difference on the bias of same total charging time, because of larger time-averaged heat generation rate than constant current charging. Suggestions on battery geometry optimizations for both prismatic/pouch battery and cylindrical battery are proposed to reduce the maximum temperature and mitigate the temperature gradient within the lithium ion battery.

1. Introduction

In recent years, large format lithium ion batteries have caught considerable attention for the applications on electrical vehicles and hybrid electrical vehicles which demand a high-energy and high-power energy storage system, because batteries with increased size and capacity are superior to small cells in reducing the number of interconnectors and control circuits when integrated in a battery pack [1]. The capacity of commercial large format lithium ion batteries can be up to 100 Ah for cylindrical lithium ion battery [2] (spiral-wound, Shin-Kobe Electric Machinery Co., Ltd., Japan) and 200 Ah for prismatic battery (stacked plate, Thunder-Sky Green Power Source Co., Ltd., China).

As the cell size increases, key concerns for both manufacturers and designers of battery pack thermal management system are the high temperature and large temperature gradient, as well as the spatial non-uniformity of current and state of charge within batteries [3]. The above issues, which are especially significant during fast charging process, have made the scaling-up of batteries challenging though the technology of small lithium ion batteries has made significant progress regarding performance, cost, life and safety in the past 20 years [1]. The well-known reason for large temperature gradient in a large format battery is the decreased surface-to-volume ratio and the low cross-plane (and radial-direction in cylindrical battery) thermal conductivity, as well as the high heat generation rate of the battery. And discrete electrical tabs effect and temperature gradients within the battery would lead to the spatial non-uniformities of current and state of charge. Poor battery design of large format cells may cause non-uniform utilization of the active material and would strongly affect the current distribution, state of charge, voltage and temperature distribution, which may lead to a local degradation of the battery, reducing its performance and cycle life [4,5]. Therefore, a good cell design is essential to reduce the non-uniformities and to improve the battery performance.

Numerical modeling has long been an economical and fast method for investigating the battery performance, and for optimizing the cell design and shortening design processes. However, most of the existing thermal modeling in the literature are the lumped-scale models, which couple a 1 dimensional electrochemical model with a 1 dimensional [6], 2 dimensional [7], or 3 dimensional [8] thermal model, and are inadequate to analyze the spatial non-uniformity of current and state of charge distribution within the battery. A 2 dimensional or 3 dimensional

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Nomenclature

A	electrode plate area (m^2)
c	lithium ion concentration (mol m^{-3})
C_p	specific heat capacity (J kg^{-1} K^{-1})
D	lithium ion diffusivity (m^2 s^{-1})
E	cell potential (V)
F	Faraday constant (C mol^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
i_0	exchange current density (A m^{-2})
I	charging or discharging current of the battery (A)
j_{loc}	local current density (A m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
k_0	reaction rate constant ($m^{2.5}$ $mol^{-0.5}$ s^{-1})
K_{junc}	liquid junction potential
L_c	characteristic length for biot number
Q	volumetric heat generation rate (W m^{-3})
r	radius distance variable of particle (m)
r_p	characteristic particle radius of electrode particles (μm)
R	gas constant (J mol^{-1} K^{-1})
R_{tc}	thermal contact resistance (m^2 K W^{-1})
R_{ec}	internal electrical contact resistance (mΩ m^2)
R_{ex}	external electrical contact resistance (mΩ)
S_a	specific surface area (m^{-1})
T	temperature (K)
t_+	transference number of Li ion species dissolved in liquid
U	thermodynamic, open circuit voltage (V)
V	volume of battery (m^3)

Greek letters

α_a	transfer coefficient for anodic current
α_c	transfer coefficient for cathodic current
ε_1	active material volume fraction
ε_2	volume fraction
ϕ	electric potential (V)
γ	bruggeman tortuosity exponent
ρ	density (kg m^{-3})
σ	electrical conductivity (S m^{-1})
η	over potential (V)

Subscripts, superscripts and acronyms

0	initial or equilibrated state
1	solid phase
2	solution phase
a	ambient temperature
n	negative electrode
p	positive electrode
ref	reference composition or relative to a Li/lithium ion reference electrode
SOC	state of charge
x	spatial coordinate (m)
y	distance variable through a cell component (m)
z	spatial coordinate (m)

electrochemical thermal model would be more helpful for capturing the detail spatial electrochemical performance. Generally, a 3 dimensional model is powerful and straightforward to investigate the spatial electrochemical-thermal performance of the battery, however, has the drawbacks of consuming much more computing time and computing resources. Hence, most of the researchers chose the 2 dimensional modeling instead, to study the spatial non-uniformity of prismatic/pouch battery performance. However, most of the 2 dimensional modeling focused on the in-plane non-uniformity of battery performance, and studied the tabs effect on current distribution and temperature distribution [9–12], while spatial non-uniformity in cross-plane direction is underestimated and overlooked. It should be noted that, during fast charging process with external cooling, large temperature gradients would be generated in the cross-plane direction, the temperature-dependent electrochemical performance is supposed to vary across the cross-plane direction due to the temperature gradient. The non-uniformity in cross-plane direction would be especially significant when the thickness of prismatic/pouch cell is large, and the cross-plane thermal conductivity is low due to large layer-to-layer thermal contact resistance which is often overlooked by researchers in the modeling. Hence, it is of great significance to investigate the spatial non-uniformity of electrochemical performance in cross-plane direction, and provide suggestions for large format lithium ion battery designers to avoid unexpected loss of battery performance.

This study aims to shed some light on the design of large format lithium ion batteries. In this work, a two dimensional electrochemical thermal model was developed on the cross-plane of a laminated stack plate prismatic/pouch lithium ion battery, the effect of thermal contact resistance on the thermal performance of lithium ion battery was examined, and the influence of temperature gradient on the electrochemical performance of within a lithium ion battery was also studied. A pulse charging protocol was evaluated comparing to constant current charging in terms of heat generation rate and temperature rise during charging. Suggestions on battery geometry optimizations for both prismatic battery and cylindrical battery were proposed to reduce the maximum temperature and mitigate the temperature gradients within the lithium ion battery.

2. Model development

In this study, a local distribution model for pouch cells, and a lumped scale electrochemical model for cylindrical batteries were developed for the investigation of the effect of thermal contact resistance on the performance of both types of batteries.

Firstly, for the study of cylindrical cell, a lumped scale electrochemical-thermal model which couples a 1 D electrochemical model and a 2 D thermal model developed in our previous study [7] was extended to the current study on the effect of thermal contact resistance.

For the study of pouch cell, 2 dimensional models in open literatures focused on the in-plane (xz planes in Fig. 1(c)) non-uniformity of pouch cell performance caused by small current collector lead-tabs (on the same terminal of the battery) [9–11] as shown in Fig. 1(a). In this study, in order to waive the consideration on the in-plane (xz planes in Fig. 1(c)) non-uniformity and highlight the cross-plane (xy planes in Fig. 1(c)) non-uniformity of the battery, the stacked plate pouch cell chosen for this study has large current collector lead-tabs on opposite terminals as shown in Fig. 1(b) and (c) [13]. The 2D model is on the yz cut plane of the battery and details of the cut plane geometry are shown in Fig. 1(d). The designed pouch battery (20 Ah, height 175 mm, width 76 mm, thickness 21 mm) is a laminated stack plate assembly of a number of cell units comprising positive current collector, positive electrode, separator, negative electrode, and negative current collector (labeled as pc/pe/sp/ne/nc, respectively).

The electrochemical-thermal model was first developed by Doyle and Fuller et al. [14,15] using porous electrode theory, and the model in this study is developed following the work of Somasundaram et al. [16] and the work of Ye et al. [17]. The governing equations are tabulated in Table 1. The charge balance of the solid phase and solution phase can be computed from Eqs. (1) and (2),