

Prediction of Temperature Field Inside Lithium-Ion Battery Based on Similarity Theory

Lijun Zhang, Hongzheng Cheng, Kun Diao, and Cheng Ruan
Tongji Univ.

ABSTRACT

To accurately and efficiently predict the temperature fields inside a lithium-ion battery is key technology for the enhancement of battery thermal management and the improvement of battery performances. The dimensional analysis method is applied to derive similarity criteria and the similarity coefficients of battery interior temperature fields, based on the governing partial differential equations describing the three dimensional transient temperature field.

To verify the correctness of similarity criteria and the similarity coefficients, 3D finite element models of battery temperature field are established with a prototype and scale model, on the assumption that the battery cell has single-layer structure and multi-layers structure separately. The simulation results show that the similarity criteria and the similarity coefficients are correct. The calculation efficiency is checked to be much more efficient compared with FEM model based on the original cell structure in aspect of amount of resources occupied.

Then the thermal behavior of the battery cell under different discharge rates is investigated. The results indicate that temperature rise and temperature gradient are both much more significant when battery undergoes high-rate discharges.

Thus the finite element modeling method based on similarity theory can be applied for simulation and analysis of the temperature fields in lithium ion battery.

CITATION: Zhang, L., Cheng, H., Diao, K., and Ruan, C., "Prediction of Temperature Field Inside Lithium-Ion Battery Based on Similarity Theory," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 7(1):2014, doi:10.4271/2014-01-1841.

INTRODUCTION

Lithium ion batteries have become the primary choice for electric vehicles (EVs) because of their outstanding characteristics of long self-discharge, high energy density and high operating voltage compared to other battery technologies [1]. However, they have not yet been widely introduced in automotive products. The main barriers are safety, cost, and low temperature performance, which are all related to thermal effects in the batteries and will further influence the performance of the electric vehicles. At the present stage, modeling, testing and evaluation for the thermal performance of lithium-ion battery are one of the key technology for the enhancement of battery thermal management and improvement of battery performances [2, 3, 4].

Prismatic battery cell consists of five thick layers: cathode current collector, cathode active material, separator, anode active material, anode current collector, as shown in Figure 1. The thickness (z direction) of each layer is in the scale of micron meters, while the length (x direction) and width (y direction) are in the scale of decimeter. This demonstrates that the cell structure has remarkable characteristic of multi-scale.

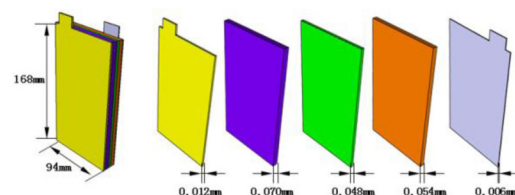


Figure 1. Structure of lithium-ion battery cell

In recent years, finite element method (FEM) tends to become one of the most commonly used tools to predict the temperature fields of lithium ion battery [4]. 1D [5, 6, 7, 8, 9], 2D [10,11], 3D [12, 13, 14] thermal models of lithium ion battery have been presented in literatures. Compared with 1D and 2D model, 3D thermal model can provide more precise prediction of temperature in battery. However, 3D thermal models presented were mostly established on the basis of simplifying assumptions: 1. the structure to a kind of anisotropic material with single-layer structure [12, 13, 14]. 2. The heat generation was assumed to be uniform in the whole volume of the battery [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

In fact, a lithium ion battery is usually consists of hundreds of cells which have five -layer structure, and the thermal property of each layer varies widely. The heat generation is not even due to the uneven electro-chemical reaction rate in the volume. Therefore, under certain operation conditions, the temperature distribution is uneven in the cell or battery.

However, because of the multi-scale characteristics of battery cell, establishing the finite element model directly with the original structure brings about difficulties during calculation, including large numbers of elements and significant calculation resource. Therefore, solving the modeling difficulties brought by multi-scale characteristics is key to the prediction of 3D temperature field in battery by finite element method. In this paper, a finite element model based on similarity theory is proposed to address this problem.

Similarity theory is one modeling method developed by human during the process of exploring the law of the nature. It has made remarkable contribution to the development of fluid mechanics [16], heat transfer theory, and also other fields of engineering [17, 18]. However, up to now, there has yet any published research that applies similarity theory to the modeling of physical fields of battery.

In this paper, the finite element method based on similarity theory is presented.

The dimensional analysis method is applied to derive the similarity criterions and similarity coefficients of temperature fields with the governing partial differential equations describing the 3D transient temperature field in battery. The correctness of similarity criterions and similarity coefficients are verified with 3D finite element models of temperature field in ANSYS software. Then based on the model established, the thermal behavior of cell during different discharge rate is investigated, also the calculation efficiency is evaluated. Thus the modeling method proposed in this paper lay a foundation for the object-oriented modeling, analysis and optimization of the lithium ion battery cell thermal performance

DERIVATION OF SIMILARITY CRITERIONS OF TEMPERATURE FIELD

Similarity Criterions Derivation

The heat generation, conduction and dissipation in lithium ion battery is a typically 3D transient thermal process. To predict the temperature field inside lithium ion battery, the partial differential equations (PDE) of 3D transient thermal process are established [19] as follows:

①governing equation:

$$\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

②the third kind of boundary conditions:

$$\begin{cases} x=0, \frac{\partial T}{\partial x}=0; & x=a, \lambda_x \frac{\partial T}{\partial x} = h_x (T - T_f) \\ y=0, \frac{\partial T}{\partial y}=0; & y=b, \lambda_y \frac{\partial T}{\partial y} = h_y (T - T_f) \\ z=0, \frac{\partial T}{\partial z}=0; & z=c, \lambda_z \frac{\partial T}{\partial z} = h_z (T - T_f) \end{cases} \quad (2)$$

③initial condition:

$$t=0, T(x, y, z, t) = T_0 \quad (3)$$

Where $\lambda_x, \lambda_y, \lambda_z$ are the thermal conductivity in x,y,z direction. T is the temperature, q is the inner heat generation rate, ρ is the density, C_p is specific heat capacity of material at constant pressure, h_x, h_y, h_z are the coefficients of convective heat transfer.

In order to nondimensionize [equation 1, 2, 3](#), the reference quantities of length, time and temperature are introduced. The reference length are $\delta_x, \delta_y, \delta_z$, respectively in each direction, listed as follows,

$$\delta_x = \lambda_x^{\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{\frac{1}{6}} \quad (4-1)$$

$$\delta_y = \lambda_y^{\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{\frac{1}{6}} \quad (4-2)$$

$$\delta_z = \lambda_z^{\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{\frac{1}{6}} \quad (4-3)$$

The reference temperature is

$$\theta = T - T_f \quad (4-4)$$

The reference time

$$\tau = \rho C_p \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{\frac{1}{3}} \quad (4-5)$$

After introducing the reference quantities Eq.(4-1), (4-2), (4-3), (4-4), (4-5) into Eq.(1), (2), (3), the PDE of 3D transient thermal process can be transformed into the following dimensionless form

$$\frac{\partial \Theta}{\partial F_o} = \frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2} + \frac{\partial^2 \Theta}{\partial Z^2} + Q \quad (5)$$

The third kind of boundary conditions:

$$\begin{cases} X=0, \frac{\partial \Theta}{\partial X}=0; & X=A, \frac{\partial \Theta}{\partial X}=B_{ix}\Theta \\ Y=0, \frac{\partial \Theta}{\partial Y}=0; & Y=B, \frac{\partial \Theta}{\partial Y}=B_{iy}\Theta \\ Z=0, \frac{\partial \Theta}{\partial Z}=0; & Z=C, \frac{\partial \Theta}{\partial Z}=B_{iz}\Theta \end{cases} \quad (6)$$

The initial condition:

$$F_o = 0, \Theta = 1 \quad (7)$$

In the dimensionless equations 5, 6, 7,

$\Theta = \frac{\theta}{\theta_0}$ is the dimensionless temperature,

$B_{ix} = \frac{h_x \delta_x}{\lambda_x}, B_{iy} = \frac{h_y \delta_y}{\lambda_y}, B_{iz} = \frac{h_z \delta_z}{\lambda_z}$ are the Boit numbers,

referring to the dimensionless coefficients of convective heat transfer in each direction.

$F_o = \frac{t}{\tau} = t(\rho C_p)^{-1} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{3}}$ is the Fourier number, refers to dimensionless time.

$Q = \frac{q}{\theta_0} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{3}}$ is dimensionless heat generation rate;

$A = a \lambda_x^{-\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{6}}, B = b \lambda_y^{-\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{6}}$ and

$C = c \lambda_z^{-\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{6}}$ is dimensionless coordinate of convection

boundary, $X = x \lambda_x^{-\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{6}}, Y = y \lambda_y^{-\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{6}}$ and

$Z = z \lambda_z^{-\frac{1}{2}} \left(\frac{a^2 b^2 c^2}{\lambda_x \lambda_y \lambda_z} \right)^{-\frac{1}{6}}$ are the dimensionless coordinate.

Apparently, Eq. (5), (6), (7) demonstrate that the dimensionless temperature Θ is the function of dimensionless variables $B_{ix}, B_{iy}, B_{iz}, F_o, Q, X, Y, Z, A, B, C$. Therefore the dimensionless

variables can be the similarity criterions of 3D transient thermal conduction process under the third kind of boundary conditions.

Parameter Settings of Prototype and Scale Model

Similarity criterions derived in the previous part can be applied as the rules to judge the similarity between two models. It also can be applied to determine the parameters of two models in order to achieve similarity between two models.

For a prototype and a scale model with the length of z direction multiplied by N, in order that the temperature field between the prototype and scale model be similar, the similarity criterions of prototype and scaled model must be equal. Thus the parameter settings of the prototype and scale model can be determined as shown in Table 1.

Tab.1. Parameters ratios of prototype to scale model

Thermal conductivity			Convection coefficients			Heat generation rate
λ_x	λ_y	λ_z	h_x	h_y	h_z	q
1	1	N^{-2}	1	1	N^{-1}	1

When the parameter settings of prototype and scale model conforms with the requirements of Table 1, the dimensionless temperature field of prototype and scale model are the same, $\Theta_1(X, Y, Z, F_o) = \Theta_2(X, Y, Z, F_o)$. That is to say, the temperature fields of the prototype and scale model satisfy the similarity relation as follow:

$$T_1(x, y, z, t) = T_2(x, y, Nz, t) \quad (8)$$

FEM VALIDATION OF SIMILARITY CRITERIONS

FEM Validation with Single-Layer Li-Ion Cell Structure

Reference [20] proposed a method for simplifying five-layer structure into single layer structure in order to conduct thermal analysis. The equalized parameters thermal conductivity, volumetric specific heat capacity are calculated by the Eq. (9), (10), (11),

$$\lambda_x = \lambda_y = \frac{\sum \lambda_i c_i}{\sum c_i} \quad (9)$$

$$\lambda_z = \frac{\sum c_i}{\sum \lambda_i}$$

Documents
Document Sharing Hub