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Spatial-resolution, lumped-capacitance thermal model for cylindrical Li-ion batteries under high Biot number conditions

Rajib Mahamud, Chanwoo Park *

Department of Mechanical Engineering, University of Nevada, Reno, NV 89557-0312, USA

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ABSTRACT

The time-efficient yet accurate thermal modeling of the battery cells for electric and hybrid electric vehicles is essential improving the performance, safety, and lifetime of the battery system. This paper presents a spatial-resolution, lumped-capacitance (LC) thermal model for cylindrical battery cells under high Biot number ($Bi \geqslant 1$) conditions where the classical LC thermal model is generally inapplicable because of a significant temperature variation in the cell volume. The spatial-resolution LC model was formulated using zero- and first-order Hermite integral approximations. For model validation, a one-dimensional, transient analytical (exact) solution using Green functions was obtained for a cylindrical Li-ion battery cell with uniform volumetric battery heat generation of Joule and entropic heating under convective cooling boundary conditions. It was found from the comparison of the results that the spatial-resolution LC thermal model can accurately and quickly predicts the cell temperatures (core, skin and area-averaged) under various dynamic battery duty cycles even for high Biot numbers due to highly convective conditions such as liquid cooling.

1. Introduction

As electric vehicles (EVs) and hybrid electric vehicles (HEVs) are poised to become a major player in the global auto market, there is a great need of advanced thermal modeling tools for battery cells to design and operate the vehicle traction battery systems more efficiently. The traction battery systems often house several hundred to thousands of battery cells such as Li-ion and Ni-MH, which are used under dynamic electrical loading [1–3].

Battery thermal management is critical for operating the battery systems efficiently in all driving and climate conditions without causing thermal damage to the battery cells [1–4]. The Li-ion battery has recently been a popular choice for the vehicle traction battery due to its high power density and charge/discharge efficiency [5]. However, a tight temperature requirement presents a big challenge to the Li-ion battery thermal management. For example, the operating temperatures of the Li-ion battery for EVs and HEVs typically ranges from −40 to 40 °C and the cell-to-cell temperature differences are required to be below 5 °C [1,3].

The computational fluid dynamics (CFD) models and finite element models have been widely used for the battery thermal analysis [1,3,6,7]. Multi-dimensional CFD modeling is often a difficult task because of complex modeling steps such as solid modeling, meshing, intense computation and post-processing. It is sometimes very time-consuming and impractical to run

* Corresponding author. Address: Department of Mechanical Engineering, University of Nevada, Reno 1664 N. Virginia Street, Reno, NV 89557-0312, USA. Tel.: +1 775 682 6301; fax: +1 775 784 1701.

E-mail address: chanwoo@unr.edu (C. Park).

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Nomenclature

A	area [m^2]
Bi	cell Biot number, Bi = $h_f R/k_s$
c_p	specific heat capacity [J kg $^{-1}$ K^{-1}]
D	diameter of a battery cell [m]
dE_{oc}/dT	entropic coefficient [mV K^{-1}]
E	cell potential [V]
G	Green function
H	Hermite integral approximation
h	convective heat transfer coefficient [W m^{-2} K^{-1}]
I	battery electrical current [A]
J	Bessel function of the first kind
$M_{[kg]}$	thermal conductivity [W m^{-1} K^{-1}]
L	length [m]
R	radius [m]
R_e	internal electrical resistance of a battery cell [mΩ]
r	radial dimension [m]
r'	instantaneous location [m]
S	heat generation [W]
SOC	state of charge [%]
s	volumetric heat generation [W m^{-3}]
T	temperature [K]
t	time [s]
V	volume [m^3]
x	negative electrode stoichiometry constant
y	positive electrode stoichiometry constant
z	axial dimension [m]

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
β	eigenvalue
ρ	density [kg m^{-3}]
φ	homogenous solution
τ	time or period of charging and discharging [s]

Subscripts

0	zero-order Bessel function
1	first-order Bessel function
a	ambient condition
avg	area-averaged
c	core
e	electrical
f	fluid phase
i,j	order of Hermite integral approximation
irr	irreversible
m	dummy index $(1,2,\ldots,\infty)$
o	initial condition
oc	open circuit
p	pressure
r	battery reaction
rev	reversible
s	heat generation and solid phase or skin
x,y	electrode stoichiometry constants

Other symbols

-	time-averaged
∞	ambient condition or infinity