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Modeling of the transient behaviors of a lithium-ion battery during dynamic cycling☆

Jaeshin Yi [a], Jeongbin Lee [a], Chee Burm Shin [a, *], Taeyoung Han [b], Seongyong Park [c]

[a] Dept. of Chemical Engineering and Division of Energy Systems Research, Ajou University, Suwon 443-749, Republic of Korea
[b] Vehicle Development Research Lab., GM R&D Center, Michigan 48090-9055, USA
[c] R&D Korea Science Officer, GM Korea, Inchon 403-714, Republic of Korea

HIGHLIGHTS

- The transient behaviors of a lithium-ion battery are predicted during dynamic cycling.
- Lumped double-layer capacitance is included to account for transient effects.
- The transient behaviors from modeling agree well with the experimental measurements.

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ABSTRACT

In this paper, we report a modeling methodology on the transient behaviors of a lithium-ion battery (LIB) during dynamic cycling. To account for the short time effects of current pulses and rest periods, the nonfaradaic component of the current density transferred through the separator between the positive and negative electrodes is included based on the lumped double-layer capacitance. Two-dimensional modeling is performed to predict the transient behaviors of an LIB cell during dynamic cycling. To validate the modeling approach presented in this work, modeling results for the variations in cell voltage and two-dimensional temperature distribution of the LIB cell as a function of time are compared with the experimental data for constant-current discharge and charge cycles and the Heavy Duty Urban Dynamometer Driving Schedule cycles. The transient behaviors obtained from the modeling agree well with the experimental measurements.

1. Introduction

The lithium-ion battery (LIB) is growing in popularity for the automotive applications such as hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs) because it has a relatively higher energy density, longer cycle life, and lower self-discharge rate as compared to other cell chemistries. The main barriers to the deployment of large fleets of vehicles on public roads equipped with LIBs are related to the thermal issues in LIBs as Bandhauer et al. [1] pointed out in their critical review. The battery life and performance of LIBs including the cell voltage, discharge capacity, and power capabilty depend strongly on the temperature of the battery cell. It is, therefore, important to calculate accurately the uneven temperature distribution of the battery cell under dynamic driving cycles for HEV and BEV applications to control the temperature of an LIB cell within a suitable range. Modeling can play an important role for exploring various battery pack cooling strategies in HEV and BEV applications [2,3].

There have been many previous works on the modeling of LIBs and the reviews of LIB models are given in Refs. [4–7]. Doyle et al. [8] developed a porous electrode model of the lithium polymer battery (LPB) based on the concentrated solution theory. Others [9–16] used or modified the model of Doyle et al. [8]. Kwon et al. [17] presented a different approach from the rigorous porous electrode model [8–16] to predict the discharge behavior of an LIB cell. They developed a two-dimensional model to calculate the potential and current density distribution on the electrodes of an LIB cell during constant current discharge by solving the equations derived from the principle of charge conservation. Although they did not include the potential distribution in the electrolyte phase

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* Corresponding author.
E-mail address: cbshin@ajou.ac.kr (C.B. Shin).

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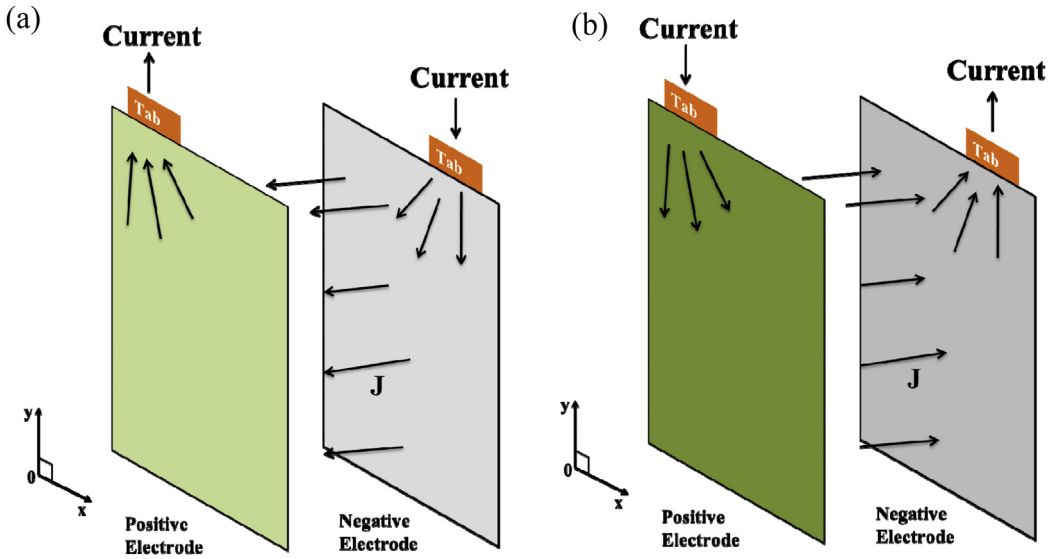

Fig. 1. Schematic diagrams of the current flow in the parallel plate electrodes of a battery (a) during discharge and (b) charge.

and the lithium ion transport in their model, the modeling results are in good agreement with the experimental data. By not calculating the distributions of the electrolyte-phase potential and lithium ion concentration, the model of Kwon et al. [17] saves significant computational time as compared to the rigorous porous electrode model, while maintaining the validity of the model, even at high discharge rates. Kim et al. [18–20] performed two-dimensional thermal modeling to predict the thermal behaviors of an LIB cell during discharge and charge on the basis of the potential and current density distributions obtained by the same procedure used by Kwon et al. [17]. They reported good agreement between the modeling results and experimental IR measurements. Kim et al. [21] and Yi et al. [22] extended their thermal model [18,19] to accommodate the dependence of the discharge behavior on the environmental temperature.

The modeling approach mentioned above [17–22] basically adopts the governing equations valid for a steady state and it is useful for the analysis of the battery behaviors during constant-current discharge and constant-current/constant-voltage charge. There are, however, frequent rest periods and pulse operations of high-current charge and discharge due to the regeneration of braking energy and high power extraction in HEV and BEV applications. In order to model the battery performance during dynamic cycles for HEV and BEV applications, the modeling approach should accomodate the short-time effects of current pulses and rest periods. In this work, the approach of the previous works [17–22] is extended to predict the transient behaviors of an LIB cell during dynamic cycling. Modeling results for the variations of the cell voltage and two-dimensional temperature distribution of the LIB cell as a function of time during dynamic cycling are to be compared with the experimental measurements to validate the modeling approach presented in this work.

2. Mathematical model

A prismatic pouch-type LIB fabricated by LG Chem. is modeled in this work. The LIB has a nominal capacity of 14.6 Ah and is composed of $LiMn_2O_4$ positive electrodes, graphite negative electrodes, and porous separators impregnated with plasticized electrolyte. A cell consisting of two parallel plate electrodes of the battery shown in Fig. 1 is chosen for modeling, because an LIB consists of multiple alternating layers of positive and negative electrode plates and separators. Fig. 1(a) and (b) show schematically the current flows in the cell during discharge and charge, respectively. The distance between the electrodes is assumed to be so small that the current flows between the electrodes are perpendicular to the electrodes. The modeling procedure adopted in this work to calculate the potential and current density distribution on the electrodes is similar to that of the two-dimensional model of Kwon et al. [17]. From the continuity of the current on the electrodes during discharge, the following Poisson equations for the potentials in the positive and negative electrodes can be

Table 1
Fitting parameters used to calculate the potential and current density distributions on the electrodes during charge.

Parameter	Value
a_0 (V)	4.135
a_1 (V)	−0.91
a_2 (V)	1.405
a_3 (V)	−1.48
a_4 (Am^{-2})	116.859
a_5 (Am^{-2})	−892.8001
a_6 (Am^{-2})	5250.46
a_7 (Am^{-2})	−13623.09
a_8 (Am^{-2})	15853.17
a_9 (Am^{-2})	−6757.8539

Table 2
Fitting parameters used to calculate the potential and current density distributions on the electrodes during discharge.

Parameter	Value
a_0 (V)	4.12
a_1 (V)	−0.804
a_2 (V)	1.075
a_3 (V)	−1.177
a_4 (Am^{-2})	116.859
a_5 (Am^{-2})	−892.8001
a_6 (Am^{-2})	5250.46
a_7 (Am^{-2})	−13623.09
a_8 (Am^{-2})	15853.17
a_9 (Am^{-2})	−6757.8539