Cycle life analysis of series connected lithium-ion batteries with temperature difference

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HIGHLIGHTS

- A cycle life model is proposed to simulate the capacity fade of LIBs.
- We simulate the discharge curve of series connected LIBs.
- Increased temperature difference among cells decreases the pack capacity.
- The adverse effect of temperature is experimentally verified.

ARTICLE INFO

ABSTRACT

Within a battery pack of electric vehicles, a constant and homogeneous temperature distribution is an ideal case. However, what is in fact frequently observed is an unbalanced cycle life performance between series/parallel connected cells. While previous studies have proposed models that simulate the capacity fade of a single lithium-ion battery (LIB) in cycle life tests, most of them do not consider the accompanying effects when batteries are connected, and these models could only investigate cycling under a constant cell temperature. To analyze the temperature difference effect on a battery pack, we develop a cycle life model that allows for temperature variation of LIBs during cycling, and we apply the model to the simulation of series connected LIBs based on the porous electrode theory. We assign different hypothetical temperatures to each of the cells in series. Such a design generates a state of performance imbalance. Our result shows that the capacity degradation of the battery pack increases with the increase of temperature difference and of the average temperature. We then conduct an experiment to verify this adverse effect. The experimental data agree well with the simulation result.

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1. Introduction

With an innate advantage of no memory effect and high power density, lithium-ion battery (LIB) is currently an ideal power source for electric powered vehicles [1–4]. However, one of the major concerns that limits the application and market of LIB in electric transportations is the life span of the cells. This cells' life span, which is often identified as the cycle life performance in the study of LIB, is highly determined by the cells' working temperature

condition. Therefore, battery thermal management has been an important topic in the field of LIB application.

In industrial applications, a high voltage and power is usually required; hence, we need a battery pack that is composed of several batteries connected in series and parallel. Due to the cell layout inside the pack, the ideal scenario of no temperature difference is difficult to achieve. That is, it is challenging to keep uniform temperature between individual cells. Although it is well known that temperature difference will affect the capacity of battery pack [5,6], the degree of this influence yet requires further qualitative and quantitative analysis. Such analyses can be performed with the aid of battery pack simulation, which includes the modeling of LIB capacity fade and battery series/parallel connection.

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Since cycle life degradation is mainly contributed by the side reactions of lithium-ion and electrolyte, the induced irreversible current, which may co-exist with the reversible current, can be considered as the cause of the capacity fade [7–10]. Put differently, the irreversible reaction triggers a continuous loss of active material during every cycle. Therefore, numerical modeling of this process can also be achieved by decreasing a specific amount of the initial lithium-ion concentration before each discharge [11]. Another option to simulate LIB cycle life is to use the single particle model [12]. This alternative approach is to concentrate only on modeling the SEI growing behavior at the porous negative electrode's surface and calculate the equivalent battery capacity loss. Other cycle life simulations also take temperature into account [13,14], as experiments have shown that a higher cell temperature results in a poorer cycling ability [13].

Although numerous studies have presented models that can simulate the capacity fade of an LIB [7–15], a majority of them are limited to the assumption of constant battery temperature, which is difficult to maintain for a large C-rate discharge. Moreover, this isothermal assumption deviates far from the situation of an LIB in practice, where various factors can cause the battery temperature to fluctuate frequently and severely. For this reason, it is necessary to develop a new model with the ability to consider the temperature variation of an LIB. On the other hand, there may be dozens of cells connected in series/parallel within a particular battery pack; however, simulations of series/parallel connected LIBs were seldom performed, especially by an electrochemical approach. Consequently, a simulation of series/parallel connected battery that takes temperature as an important parameter would be critical in the study of LIB pack cycle life performance.

It has been known that both parallel and series connection have additional, probably negative, effects on the battery pack's performance. However, they affect the pack performance in distinct ways. Different from a series-connected pack where cells share the same value of electric current, the current in a single battery of a parallel-connected pack could differ from each other due to mismatching resistance that might be induced by unbalanced temperature between cells. The topic of mismatching internal resistance of cells has recently been studied with experiments [16], and it has been shown that matching resistance of cells is crucial in the cycle-life of a parallel connected pack. Accordingly, one of the key issues to be explored in modeling a parallel-connected pack is to find a robust or efficient way that could renew or adjust the distribution of total electric current in accordance with the timely change in cell's impedance. The aforementioned issues of a parallel-connected pack deserve an independent study and are therefore beyond our scope. In this paper, for simplicity of analysis and for the sole purpose of evaluating the effect of temperature difference on the cycle life performance of a battery pack, we focus our attention on a series connection.

The study models a battery pack that consists of ten series connected cells. The batteries are 26650 lithium iron phosphate (LFP) 2.3 Ah LIBs, a type of cell that has received great interest in the recent years in both academic and industrial fields [13,14,17–25]. Based on the porous electrode theory, we develop a numerical model which allows variation of temperature. First, we find the discharge curve for a single LIB. The capacity fade is described by a newly proposed Arrhenius type equation, which accounts for the irreversible decrease in the lithium-ion concentration of negative electrode in the discharge process. Afterward, to investigate the temperature difference effect on the pack's cycling performance, this single LIB model is applied to a series-connected pack, where a temperature distribution of the assembly is specified.

Conducting a full-scale experiment of cycling multiple connected batteries of different temperature will take a considerable amount of time. However, in order to verify the result of our simulation, we conduct a smaller-scale experiment, where two cells are connected in series, to examine whether temperature difference has an effect on the performance of the batteries. The model developed here can be used to estimate the performance of a battery pack with specific thermal management by simulation. Accordingly, this work could provide a relatively time- and money-saving solution for the development of battery packs.

2. Galvanostatic discharge curves of an LIB

Based on a series of works by Newman's group [26–30], the porous electrode theory is currently widely used in simulating the electrochemical process of LIBs. The model simplifies the jelly-roll of the cell to a one-dimensional geometry that is composed of five segments which correspond to the thickness of two current collectors, of two electrodes, and of a separator. Fig. 1 is an example of the one-dimensional structure, where the leftmost boundary of the left current collector is set as the origin of the x-axis in our study.

The solid phase materials of the porous electrodes are treated as a series of lithium containing spherical particles aligned along the x-axis. In the solid phase the mass transfer of lithium can be described by the spherical Fick's laws of diffusion which occurs within the particle at position x:

$$\frac{\partial C_{s,i}(x,r,t)}{\partial t} = D_{s,i}\left[\frac{\partial^2 C_{s,i}(x,r,t)}{\partial r^2} + \frac{2}{r}\frac{\partial C_{s,i}(x,r,t)}{\partial r}\right], i = n, p, \quad (1)$$

where $C_{s,i}$ is the concentration of lithium in the i electrode, $D_{s,i}$ is the solid phase lithium diffusivity, r is the radial coordinate of the electrode's particle, and the subscripts n and p denote the negative and positive electrode, respectively.

At the surface of the electrodes, the net pore wall flux of lithium-ion can be evaluated by the Butler−Volmer equation

$$j_i = k_i(c_i)^{0.5}\left(C_{s,i,\max} - C_{s,i,\text{surf}}\right)^{0.5}\left(C_{s,i,\text{surf}}\right)^{0.5} \times \left[\exp\left(\frac{F\eta_{s,i}}{2RT}\right) - \exp\left(\frac{-F\eta_{s,i}}{2RT}\right)\right], \quad i = n, p,$$
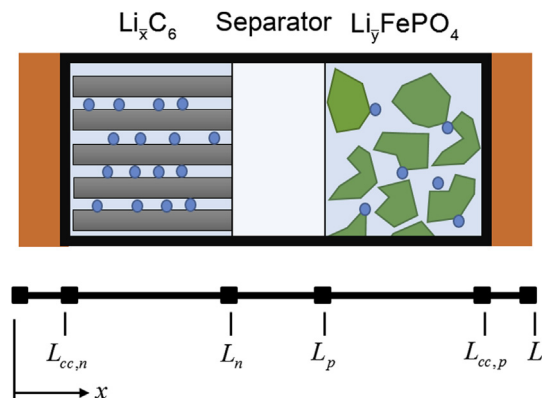
$$(2)$$

Fig. 1. The one-dimensional geometry of porous electrode theory.