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Unbalanced discharging and aging due to temperature differences among the cells in a lithium-ion battery pack with parallel combination

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HIGHLIGHTS

- A thermal–electrochemical model is developed for the parallel-connected cells.
- Temperature differences among the cells cause unbalanced discharging and aging.
- A greater temperature difference results in a larger capacity loss of the pack.

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ABSTRACT

This paper presents an investigation on the unbalanced discharging and aging due to temperature difference between the parallel-connected cells. A thermal–electrochemical model is developed for the parallel-connected battery pack. The effects of temperature difference on the unbalanced discharging performances are studied by simulations and experiments. For the parallel-connected cells, the cell at higher temperature experiences a larger current in the early discharging process before approximately 75% of depth of discharge (*DOD*). When the discharge process approaches the voltage turn point of the battery pack, the discharge current through the cell at higher temperature begins to decrease significantly. After the *DOD* reaches approximately 90%, the discharge current of the cell at higher temperature rises again. Correspondingly, the changes in the discharging current through the cell at lower temperature are opposite to that of the cell at higher temperature. Simulations also show that the temperature difference between the parallel-connected cells greatly aggravates the imbalance discharge phenomenon between the cells, which accelerates the losses of the battery pack capacity. For the parallel-connected battery pack, the capacity loss rate approximately increases linearly as the temperature difference between the cells increases. This trend is magnified with the increase of operating temperature.

1. Introduction

Lithium-ion batteries show a great potential for powering electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to their superior energy density, high specific energy and no memory effect etc. [1]. It is widely known that the operating temperature gives significant effects on the charging/discharging performances (e.g., voltage platform, discharge capacity and service life, etc.) of the lithium-ion batteries [2–5]. A lower operating temperature (<20 °C) leads to the reductions of the battery power capability and driving range, and even the freezing phenomenon with electrolyte. On the other hand, the battery capacity degradation is aggravated when operating at extreme high temperatures (>45 °C), which may induce occurrence of the battery thermal runaway. Therefore, a thermal management system is essential for maintaining the temperature of the cells in the battery pack at desired levels. Usually, the optimal operating temperature for the lithium-ion batteries is in the range of 20 °C–45 °C, which enables to maximize the battery power (or capacity) capability and lifetime.

A few types of battery thermal management system (BTMS) have been reported in Refs. [6–14], primarily including the air-based thermal management system [6–10], the liquid-based thermal management system [11,12], and the phase change material (PCM) thermal management system [13,14] etc. Because of the

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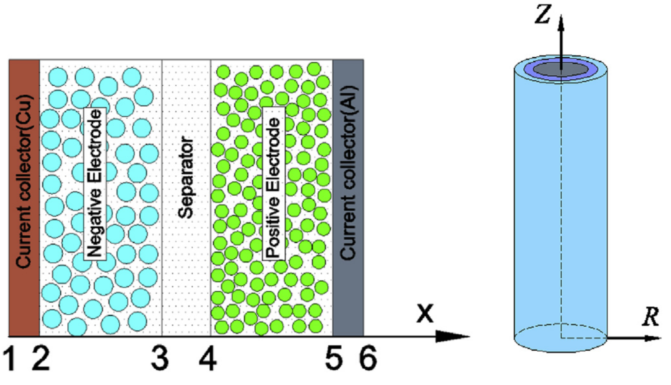
advantages of ease of operation, low production costs and little space occupation, the air-based thermal management system has been widely applied in the EVs or HEVs [14]. In the air-based cooling systems, the air is channeled from the heat exchanger into a series of ducts or channels that drive the air through the cells or modules forcing the heated air out of the battery pack and back into the heat exchange system. When the EVs drive at higher ambient temperature (>35 °C) or consume larger power (accelerating or climbing), the air-based cooling system is required to lower the inlet air temperature or increase the cooling air flux to avoid the battery overheat. This increases the temperature differences within the battery pack, leading to unbalanced discharging phenomenon among the cells. In addition, the cells far from the cooling air inlet have relatively higher temperature that results in greater capacity degradation rate [15–17], which induces the unbalanced aging phenomenon among cells in the battery pack. This divergence of cells greatly shortens the total deliverable capacity and the service life of the battery pack. An important target for BTMS design is to minimize the temperature differences among the cells in the pack.

A battery pack for EVs or HEVs is formed by a multitude of cells connected in series or/and parallel to deliver the desired driving power and capacity. The uneven temperature distribution within the pack leads to mismatch of the internal resistance among cells. For a battery pack with series combination, all the cells have the same charging/discharging current. The cutoff voltage is determined by the weakest cell among the serial-connected cells, which thus affects the overall capacity of the battery pack [18]. Unlike the series-connected cells, the current differences among the cells with parallel combination are caused by the mismatch of the cell internal resistance. The unmatched internal resistance among the parallel-connected cells causes unbalanced discharging and ageing performances. Generally, the current in each parallel-cell branch is not all monitored in the EV battery management systems. Pre assessments of unbalanced discharging and aging performances due to temperature differences among the cells are essential in the battery assembly and design of thermal management systems.

The discharging performances for different cell assembly configurations were studied by researchers [19,20]. Wu et al. [19] proposed a semi-experimental method for calculating the discharging voltage and capacity of cells in series and/or parallel-connected battery pack. However, the effects of the temperature difference within battery pack on the cell unbalanced discharging were not considered in their work. R. Gogoana et al. [20] experimentally investigated the effects of the internal resistance mismatch of cells on the discharging performances for a parallel-connected battery pack. This work is devoted to study the effects of temperature difference on the unbalanced discharging and aging performances in the parallel-connected cells. A thermal–electrochemical model is developed and is used to simulate the discharging process of the battery pack with parallel combination. The influences of the temperature differences between the parallel-connected cells on the discharging performances are analyzed in detail. An experiment-based simplified capacity degradation model is developed for the lithium-ion battery. The dependence between the cell temperature difference and the capacity loss rate is quantified for the battery pack with parallel combination.

2. Model development

The electrochemical-thermal model of lithium-ion batteries is developed on the basic of the mass conversion equations, the charge conversion equations [21–23] and the energy balance equation [23,24]. A schematic diagram of the battery electrochemical-thermal model is illustrated in Fig. 1, which includes a presudo 2D electro-chemical model in the electrode thickness scale (see Fig. 1(a)) and a 2D thermal model in the single battery scale (see Fig. 1(b)). The main components of a unit cell consist of a negative electrode, a separator, a positive electrode, bound by two current collectors. The basic assumptions of the proposed model are listed as follows:



(a) (b)

Fig. 1. Schematics of the lithium-ion battery thermal–electrochemical model: (a) Electrochemical model and (b) Thermal model.

(a) Active materials in two electrodes are considered to be composed of spherical particles with uniform size.
(b) The electrolyte is assumed to be binary with only Li^+ as the electroactive special.
(c) Electrochemical performance along the spiral direct is assumed to be homogenous.
(d) Side reaction during discharging/charging process is neglected.

Based on the above assumptions, the battery energy equation is calculated in a 2D axis-symmetric model [23].

2.1. Governing equations

2.1.1. Mass conversion equations

According to the Fick's 2nd law, the mass conservation of Li in the active particles of both electrodes is expressed by

$$\frac{\partial c_{s,i}}{\partial t}=\frac{D_{s,i}}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial c_{s,i}}{\partial r}\right) \tag{1}$$

where $i=$ n and p. The boundary conditions are described by

$$-D_{s,i}\frac{\partial c_{s,i}}{\partial r}\bigg|_{r=0}=0 \tag{2}$$

$$-D_{s,i}\frac{\partial c_{s,i}}{\partial r}\bigg|_{r=r_{s,i}}=j_i \tag{3}$$

According to the concentrated solution theory, the mass conservation of Li^+ in the electrolyte is given by

$$\varepsilon_{l,i}\frac{\partial c_i}{\partial t}=D_{eff,i}\frac{\partial^2 c_i}{\partial x^2}+a_i(1-t_+)j_i \tag{4}$$

where $i=$ n, s and p. The effective diffusion coefficient of Li in the electrolyte, D_{eff}, is given by $D_{eff,i}=D\varepsilon_{l,i}^{brug}$, which takes into account the effect of tortuosity on Li^+ transportation. The specific surface area of electrode particles is calculated by $a_i = 3\varepsilon_{s,i}/r_{s,i}$. The boundary conditions are given by