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Developing heat source term including heat generation at rest condition for Lithium-ion battery pack by up scaling information from cell scale

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ABSTRACT

Heat generation during cycling of Lithium-ion batteries may have negative effects on the efficiency, safety, performance and lifetime of battery cell due to overheating. Therefore, temperature distribution should be controlled by the battery thermal management techniques. To improve accuracy of temperature control methods, the value of heat generation should precisely be calculated. However, detail modeling of phenomena, inside all cells of a battery pack, is a time consuming process, impracticable for control purposes. The prime objective of this paper is to propose a developed analysis viewpoint of heat generation phenomenon at pack scale by presenting a relation derived from the cell scale analysis without missing the accuracy along with vanishing computational cost. In order to increase the accuracy, firstly, the thermal modeling part at cell scale is improved to consider the heat of mixing and enthalpy heating terms as significant heat sources continue to be generated after cutoff current. Then, based on output data of the corrected code, a relation for heat generation source term is estimated by neural network method. Finally, this relation is used as a source term in pack scale equations. The results demonstrated the importance of considering heat of mixing and enthalpy heating in the pack scale modeling in a wide range of cooling air flow rates. This method is generic and vanishes the computational cost of transferring information from cell scale to the pack one.

1. Introduction

Due to high energy density, long cyclic life and no memory effect, lithium ion (Li-ion) battery is one of the main candidates for utilizing in electric and hybrid vehicles [1]. Moreover, when the support policies is executed, employing Li-ion battery packs seem economical for time shifting and peak shaving in the electrical networks [2]. However, the technology still deals with some issues such as heat generation during charging and discharging processes.

Inside the active materials of Li-ion battery electrodes, electrochemical oxidation-reduction reactions take place during the charging and discharging processes and so, chemical energy converts to the electrical energy and vice versa. The processes is associated with heat generation [3] involving negative effects on the efficiency, reliability, performance and lifetime of battery cells [4]. Overheating even may results in severe safety issues due to thermal run away [5]. Allowable increasing battery temperature range during the charging and discharging and operating temperature have been reported as 5–10 °C and 25–40 °C, respectively [6]. Temperature distribution should be controlled by the battery thermal management techniques, especially in large scale applications such as battery packs used in electric (EV) and hybrid electric vehicles (HEV) and stationary energy storage systems. In order to control the temperature, the system thermal behavior modeling is very important [7] and the amount of heat generation should precisely be calculated for improving the accuracy of the thermal models.

Different methods for calculating heat transfer source term are proposed in the literature. One of them is experimental measurements [8]. The idea of using heat pipes with Li-ion battery cells has been studied experimentally in Ref. [9] and in order to simulate the heat generation rate, aluminum made rectangular heater is used instead of Lithium Iron Phosphate ($LiFePO_4$) battery and different heat generation rates are produced by changing voltage and current of heater. Effective parameters in designing a thermal management system for a pouch type Li-ion battery were investigated in Ref. [10]. This includes the effect of distance between the cells and the rate of air flow generated by the cooling fan. In steady-state condition, temperature distribution is obtained at different discharge rates at the end of discharge and a time-averaged

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Nomenclature

A	surface area between the battery cell walls and the air flow (m^2)
C	lithium ion concentration ($mol\ m^{-3}$)
C_p	specific heat capacity ($J\ kg^{-1}\ k^{-1}$)
D	Li diffusion coefficient in phase ($m^2\ s^{-1}$)
D_H	hydraulic diameter
E	internal energy ($J\ kg^{-1}$)
L	thickness (m)
f	activity coefficient
F	Faraday's constant (96,487 $C\ mol^{-1}$)
h	specific enthalpy ($J\ kg^{-1}$)
I	current (A)
i	current density at particle–electrolyte interface and in solution ($A\ m^{-3}$)
j	electrochemical reaction rate per unit area ($mol\ m^{-2}\ s^{-1}$)
$k_e(c)$	ion conductivity coefficient ($S\ m^{-1}$)
k	conductive heat transfer coefficient ($W\ m^{-1}\ °C^{-1}$)
p	pressure (Pa)
q	heat generation rate ($W\ m^{-3}$)
Q_{irr}	irreversible heat generation (W)
Q_{rev}	reversible heat generation (W)
r	active particle radius (m)
R_f	electrical resistance ($\Omega\ m^2$)
SOC	state of charge (%)
s	stoichiometry coefficient
T	cell temperature (°C)
t	time (s)
U_{equ}	standard potential affected by solid concentration (V)
V	volume (m^3)
V_t	terminal voltage (V)
$\vec{v}$	velocity ($m\ s^{-1}$)
x	stoichiometry in the positive electrode
y	stoichiometry in the negative electrode

Greek symbols

ε	active material volume fraction (%)
Φ	potential in a phase (V)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
σ	solid phase conductivity ($S\ m^{-1}$)

Subscripts

1	electrode
2	electrolyte
+ or p	positive electrode
− or n	negative electrode
c	cell
e	electrolyte phase
f	cooling air
m	average
s	solid phase
w	cell's wall

heat generation rate is applied in the modeling, measured by an isothermal calorimeter. Panchal et al. used experimental data and artificial neural network method for modeling thermal behavior of a $LiFePO_4$ lithium ion battery [11]. Mills and Al-Hallaj designed and simulated a passive thermal management system involving a phase change material (PCM) for a commercial 2.2 A h Li-ion laptop battery pack [12]. They experimentally measured the heat generation rate at various constant power discharge rates. Greco et al. compared the passive cooling using PCMs with forced air cooling [13]. In another work, they numerically studied the effect of utilizing heat pipes on the thermal behavior of Li-ion battery [14]. In their modeling, they assumed a constant heat generation rate. Sabbah et al. used numerical modeling of Li-ion battery to represent the temperature distribution at the end of discharge process at different charge and discharge current rates [15]. They obtained the heat generation rate in the heat transfer equations by the experimental results. Fathabadi presented a design for thermal management system using two cooling ducts mounted at the both sides of each of the battery cells [16]. He employed energy conservation and heat transfer equations for calculating temperature distribution inside the battery pack. The rate of heat generated inside the battery was calculated by the method presented in Ref. [17] in which internal equivalent and entropy change are experimentally measured for different state of charges (SOCs) and different temperatures. Ling et al. determined irreversible heat generation rate by the product of the difference between open circuit and terminal voltages and current which was experimentally measured [18].

One of the drawbacks of using approximate relations obtained from experiment data is case dependency [19]. The theoretical knowledge based formulations are a more generic methodology for measuring heat generation in Li-ion batteries. Heat generation term is divided into two parts: reversible generation and irreversible one. Reversible part is resulted from the electrochemical reaction and is modeled similarly in various works done by other researchers [20,21]. However, irreversible part has been modeled in different ways in the literature. The simplest way for modeling this term is production of electrical current by internal resistance of battery. For instance, this approach was used to study the effect of liquid metal [22] and PCM application in the thermal management of battery pack [23]. However, internal resistance is not constant during charging and discharging. In some works, irreversible heat generation source term is calculated by multiplication of electrical current and deviation of the terminal voltage from the equilibrium voltage [24]. For example, thermal modeling of Lithium Cobalt Oxide/Carbon ($LiCoO_2$/C) and Lithium nickel cobalt manganese oxide/carbon ($LiNiCoMnO_2$/C) batteries were studied by the method [25]. Moreover, simulation of thermal energy management for $LiFePO_4$ battery was performed using this approach [26]. In this formulation, heat generation is modeled based on the open circuit voltage and charge/discharge current. In addition to this approximation, in some works, the effect of concentration variations on the terminal and equilibrium voltage is not considered [27]. For considering variations of the terminal and equilibrium voltages, during charging and discharging SOC should be evaluated. Karimi and Li investigated different cooling methods for the battery thermal management systems, such as natural and forced cooling with air and water and passive cooling with PCM [17]. Ohmic and entropy heating terms were obtained based on entropy variation curve with respect to SOC and changes in the internal resistance of the battery. Entropic heat generation is a significant heat source term inside Li-ion batteries models. Shadman et al. experimentally measured this term and used the results in a thermal model for simulating thermal behavior of high power 7.5 A h Lithium Nickel Cobalt Aluminum oxide ($LiNi_{0.8}Co_{0.15}Al0_{.05}O_2$) Li-ion battery [28]. Another method for calculating irreversible part of heat generation term is by using Ohm laws in the solid and electrolyte phases [29]. Uddin et al. presented an equivalent circuit model to represent the thermal behavior of cell and pack scales.