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Experimental and analytical study on heat generation characteristics of a lithium-ion power battery

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ABSTRACT

A combined experimental and analytical study has been performed to investigate the transient heat generation characteristics of a lithium-ion power battery in the present work. Experimental apparatus is newly built and the investigations on the charge/discharge characteristics and temperature rise behavior are carried out at ambient temperatures of 28 °C, 35 °C and 42 °C over the period of 1 C, 2 C, 3 C and 4 C rates. The thermal conductivity of a single battery cell is experimentally measured to be 5.22 W/(m K). A new transient model of heat generation rate based on the battery air cooling system is proposed. Comparison of the battery temperature between simulated results and experimental data is performed and good agreement is achieved. The impacts of the ambient temperature and charge/discharge rate on the heat generation rate are further analyzed. It is found that both ambient temperature and charge/discharge rate have significant influences on the voltage change and temperature rise as well as the heat generation rate. During charge/discharge process, the higher the current rate, the higher the heat generation rate. The effect of the ambient temperature on the heat generation demonstrates a remarkable difference at different charge states.

1. Introduction

Among the electrochemical energy storage systems, lithium-ion batteries, as a promising candidate, have attracted considerable attention in many power demand applications due to their advantages of large specific energy, high power density, charge/discharge cycle stability and long cycle lifetime [1,2]. With rapid development of the electric vehicles (EVs) and hybrid electric vehicles (HEVs), lithium-ion batteries have been widely used in recent years [3]. However, a large amount of heat will be generated since the electrochemical reactions and physical changes inside batteries would potentially bring out capacity fade and thermal runaway [4]. Therefore, it is crucial to have insight into the heat generation characteristics in order for maintaining safety and performance of the battery.

Many researches on the safety issues of the battery are finally ascribed to the heat generation and heat dissipation at each level of the battery system [5,6]. In order to keep the battery within an accepted temperature, an efficient thermal management system (TMS) will be needed to dissipate the heat generated. Furthermore, the heat generation rate is a necessary prerequisite for an efficient TMS design [7,8]. Thus, it is imperative to understand the mechanism of the battery heat generation characteristics and its effect on the battery performance.

Many researchers have been devoted to dealing with thermal models to determine the temperature distributions of the battery cell over the past three decades. Bernardi et al. [9] firstly developed a general thermal model on the basis of the energy balance for the battery systems. They considered that the cell temperature resulted from the interaction of the Joule heat, heat of mixing, phase-change heat and electrochemical reaction heat with component-dependent open-circuit potentials. The heat generation rate could be calculated as the temperature distribution was assumed to be uniform throughout and varied with time. Afterwards, Rao and Newman [10] presented a simplified thermal model to determine the heat generation rate for insertion battery systems. In their study, the effects of the mixing heat and phase-change heat were neglected. Utilizing the thermal model proposed by Bernardi et al. [9], the battery thermal behavior was studied by Dong and Baek [11]. It was found that the irreversible Joule heat dominated under high-rate discharge conditions, but the reversible entropic heat from electrochemical reactions accounted for the bulk of heat under low-rate discharge conditions. Forgez et al.

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Nomenclature

B	time constant, s
Bi	Biot number
c	specific heat capacity, J/(kg K)
E	open-circuit potential, V
h	convective heat transfer coefficient, W/(m^2 K)
I	current, A
l	characteristic length, m
q	heat generation rate of battery, W
Q	rate of heat generated or consumed, J
R	thermal resistance, K/W
T	temperature, K
t	time, s
U	terminal voltage, V
V	volume, m^3
x, y, z	coordinate direction vector
ΔT	temperature rise, K

Greek symbols

λ	thermal conductivity, W/(m K)
ρ	density, kg/m^3
τ	time step, s

Subscripts

amb	ambient
h	convection heat transfer
J	Joule heat
max	maximum
t	time
v	volume

Acronyms

DC	direct current
DOD	depth of discharge
EV	electric vehicle
HEV	hybrid electric vehicle
ITMS	integrate thermal management system
TMS	thermal management system
TPS	transient plane source
SOC	state of charge

[12] developed a lumped parameter thermal model of a cylindrical lithium-ion battery considering the heat generated from resistive dissipation and the reversible entropic heat as the heat generation of the battery. The internal and external resistances of the battery were calculated by a steady state method. For the heat generation, Sato [13] and Lai et al. [14] considered three different heat, they were electrochemical reaction heat, polarization heat and Joule heat. The level of the heat generated was a result of the attribution from each heat. They also investigated the variation of the irreversible and reversible heat production as a function of the depth of discharge (DOD) [14]. For a prismatic lithium-ion battery cell, Greco et al. [15] developed a simplified one-dimensional transient thermal network model using thermal circuit method linked with the thermal model of the heat pipe. In order to validate the model, they also presented a special one-dimensional analytical model and a three-dimensional simulation model. The heat generation rate in a battery cell was determined by adopting the model shown in Ref. [16]. Their results showed that the thermal network model was sufficient to predict the battery temperature distribution. Combining an analytical solution of the lumped capacitance model and thermography, Bazinski and Wang [17] calculated the rate of the heat generated inside a pouch lithium-ion battery under different rates. The internal uniform heat generation was assumed and expressed by a simple third order polynomial. However, some heat curves were not accurately modeled by a polynomial in despite of its order. Yildiz et al. [18] proposed a thermal model for a pouch lithium-ion battery only accounting for the irreversible Joule heat. The battery temperature rises calculated by the model agreed well with the experimental data. The developed simplified model of heat generation can be used to calculate the rate during constant current discharge process. Birgersson et al. [19] developed a two-dimensional transient model and studied the heat generation characteristics of 18,650 cylinder lithium-ion battery pack. It was reported that during normal discharge process the ohmic heat dominated at low-rate discharge but the reversible electrochemical heat dominated at high-rate discharge. Lin et al. [20] formulated a coupled electro-thermal model for cylindrical battery. The electrical model calculated the battery state of charge (SOC) and voltage. The heat generation was determined by the difference between the terminal voltage and open circuit voltage, along with the current. A two-state model was used to capture the lumped thermal dynamics of the battery. From the thermal models mentioned above, it can be concluded that accurately determining the heat generation of the battery would be crucial for achieving accurate prediction of the temperature distribution.

Bandhauer et al. [21] performed a comprehensive review on the heat generation rate. It was stated that there are mainly three methods to determine the heat generation rate, they are direct experimental measurement, Bernardi's prediction model and electro-thermal prediction model. Some existing experimental measurements mainly focus on the heat generation by accelerated-rate calorimetry and isothermal heat conduction calorimetry [22–25], or by measuring the overpotential and entropic heat coefficient [26]. Hallaj et al. [22] studied the heat generation characteristics of the commercial lithium-ion battery according to electrochemical calorimeter. The internal resistance and entropic change coefficient at different depth of discharges (DODs) were measured. Their results showed that endothermic phenomenon occurred during the charge. However, the heat generation rate was always positive in the discharge process. Balasundaram et al. [23] measured the total heat generation of 18,650 cell under different charge and discharge rates conditions by accelerated-rate calorimetry. For the irreversible heat generation, the intermittent pulse technique was used and the reversible heat generation was obtained from the determination of the entropic coefficient at different SOC and DOD. It was found that the reversible heat was primary at lower current rates and this should be taken into account when developing the thermal model. Saito [24] carried out an experimental study on the thermal behaviors of the lithium-ion batteries during high-rate pulse cycling and measured the heat generation rate using calorimeter method. It was found that the additional heat in high-rate pulse discharge process usually resulted from side reaction, which changed the surface characteristics of the electrode and increased the impedance. Yasir et al. [25] experimentally investigated the heat generation for a high power prismatic lithium-ion battery cell. The heat generation rate was calculated by measuring the overpotential resistances with four different methods and entropic heat generated in the cell. Calorimeter tests were also performed to compare the calculated heat generation with measured one. Bandhauer