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Experimental analysis and transient thermal modelling of a high capacity prismatic lithium-ion battery

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ABSTRACT

In this paper, a three-dimensional transient model, predicting the thermal behaviour of a 60 Ah prismatic Li-ion battery during charge/discharge cycles under natural convection, is proposed. Also, an experimental test bench is used to charge and discharge the battery at different current rates (1C, 5/6C and 2/3C) in order to track its thermal behaviour using thermocouples and heat flux sensors. The model includes heat generation and solves conduction inside the battery and natural convection as boundary condition. Some of the required parameters, such as heat transfer coefficients, thermal conductivities along y and z directions and electrical resistance, are determined using experimental data. Heat capacity, thermal conductivity along x direction and entropy change are determined based on literature. Simulated battery surface temperatures are compared to experimental measurements resulting in less than 5% relative error. Additionally, core temperatures as well as reversible and irreversible heat generations are simulated using the proposed model. Simulated total heat generation is compared to measured heat generation at steady state showing a good agreement, which makes it possible, using this simple model, to predict the maximum heat generated inside the battery, and consequently the core temperature, in order to design a suitable thermal management system.

1. Introduction

Lithium-ion batteries are the preferred electrical energy storage systems for many applications such as Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs) and smaller portable devices such as laptops and smartphones. Lithium-ion batteries have higher specific energy and higher specific power compared to other cell chemistries such as Lead-acid and NiMH (Nickel Metal Hybrid) [1]. Thus, lithium-ion batteries have been the subject of intensive studies to improve their lifetime and safety. Various researchers have studied the effect of temperature on the state of health of batteries and how high temperatures can reduce their lifetime considerably [2]. Therefore, designing a suitable thermal management system is crucial for batteries in Electric Vehicles applications. For that purpose, accurate knowledge of heat generation inside the battery is essential for the design and development of lithium-ion batteries and their thermal management system, and can be accomplished either by means of experimental tests or by modelling. Recently, Gümüşsu et al. [3] summarized the methods of dealing with heat generation into two main groups: direct measurement of heat generation using experimental setups as calorimeters and calculation of heat generation based on measured electrical properties or using electrochemical calculations. Electrochemical calculations can be used to calculate electrical properties or to determine heat generation directly. Determining heat generation using direct experimental measurements can give information regarding distribution of heat flux on the surface of the battery allowing to know where to set the thermal management system inside the battery pack.

However, experimental testing can be costly and time consuming. Electrochemical models [4–6] are based on concentrated solution theory, they have high accuracy but are relatively complex compared to electrical models. Accordingly, most of the models presented in literature are based on experimentally measured electrical properties of the battery using the energy balance equation inside a battery, firstly established by Bernardi et al. [7] in 1985 where the heat generated consists of two parts: irreversible heat (Joule heat) and reversible heat (entropic heat). Chen et al. [8] developed a three-dimensional thermal model considering the layered structure of the battery, transient conductive heat transfer and convective and radiative heat transfer at the boundaries. They compared this model with several simplified thermal models and found that the simplified model considering the core region as a homogeneous material is as good as the detailed model to predict asymmetric thermal behaviour of the battery and avoids the

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Nomenclature

List of symbols

S_u	area (m^2)
h	convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
$\dot{Q}$	heat (W)
U	voltage (V)
$\varnothing$	heat flux density ($W \cdot m^{-2}$)
I	current (A)
R_{elec}	electrical resistance (Ω)
T	temperature (K)
λ_u	thermal conductivity along u direction ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
C_P	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
$\varnothing_{vol}$	volumetric heat flux ($W \cdot m^{-3}$)
R	thermal resistance ($K \cdot W^{-1}$)
m	mass (kg)
V	volume (m^{-3})
l_i	thickness of layer i (μm)
L_u	width in u direction (m)

Subscripts

amb	ambient
conv	convective
b	battery
t	total
in	core
S	battery surface
OC	open circuit

Superscripts

*	time level p
**	time level p + 1

complicated computation of the layered-structure. Liu et al. [9] and He et al. [10] used empirical data to determine electrical parameters in order to calculate total heat generation, the authors in [10] neglected entropy considering it relatively small compared to Joule heat. A two-dimensional transient thermal model was developed by Samba et al. [11] for a lithium-ion pouch cell considering convection and radiation at the boundaries. Electrical parameters were experimentally measured in order to calculate volumetric heat generated and thermal parameters were calculated using an equivalent circuit and computing the energy balance at steady state. Damay et al. [12] proposed a three-dimensional lumped thermal model for a large prismatic lithium ion battery. The thermal parameters were determined experimentally and internal electric resistance was experimentally measured whereas entropy was calculated using experimental data from literature. Simulation results of surface temperature were in good agreement with experimental measurements. Gümüşsu et al. [3] developed a three dimensional model of a lithium ion battery under natural convection. Electrical parameters were determined experimentally while thermo-physical properties were determined by evaluating several values from literature and finding the most adequate value for each of the specific heat and thermal conductivity.

In this study, a three-dimensional transient thermal model was developed to simulate the thermal behaviour of a prismatic lithium ion battery. The model predicts temperature at any point on the surface of the battery as well as in the battery core. An experimental test bench is used to validate the thermal model. The battery incurs charge/discharge cycles until reaching thermal steady state condition. In the first part, the test bench is presented in details. Secondly, the thermal model is presented with the determination of thermal and physical properties steps and heat sources used in the energy balance equation are detailed. Finally, the experimental validation of the thermal model is presented and analysed.

2. Experimental apparatus and uncertainty

The experimental test bench used to charge and discharge the 60 Ah prismatic battery is shown in Fig. 1. The equipment used for the cycling of the battery are located at the left of the image. The electric circuit contains the studied cell, a DC power supply to charge the battery and a DC active load to discharge it. A voltmeter and a current probe are used to measure voltage and current respectively. Charge and discharge current and voltages are controlled via a LabVIEW program by the user, and electric and thermal data such as voltage, current and temperatures are recorded using a NI-cDAQ system. The battery is charged and discharged between 2.6 V and 3.4 V corresponding to approximately 0%–60% SoC at different current rates (2/3C, 5/6C, 1C). The SoC range was found by comparing the 2.6 V–3.4 V charge and discharge profile to the full charge and discharge. In order to analyse the thermal behaviour

Fig. 1. Experimental test bench.