International Communications in Heat and Mass Transfer xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Modeling and validation of temperature changes in a pouch lithium-ion battery at various discharge rates☆

M. Yildiz [a], H. Karakoc [a], I. Dincer [b]

[a] Department of Aircraft and Airframe Maintenance, Faculty of Aeronautical and Aerospace Engineering, Anadolu University, Eskisehir, Turkey
[b] Department of Automotive, Mechanical & Manufacturing Engineering, Faculty of Engineering & Applied Science, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada

A R T I C L E   I N F O

Available online xxxx

Keywords:
Lithium-ion battery
Heat generation
Temperature distribution
Thermal management

A B S T R A C T

This paper deals with the thermal modeling of temperature rise in a pouch lithium-ion battery with $LiFePO_4$ (also known as LFP) cathode material. The developed model represents the main thermal phenomena in the cell in terms of temperature change. The proposed model is validated with the collected experimental data from a module composed of 11 cells. In the conducted experiments, the different charge and discharge rates of 1/2C, 1C, 2C and 2.5C are applied. It is seen that, the increased discharge rates result in increased temperature on the surface of the battery. When the discharge rate is doubled, from 1C to 2C, cell temperatures have risen by 3.5 times. A simplified model for determining the heat generation is developed and validated with the test results.

1. Introduction

Increasing costs and concerns on environmental pollution have motivated the development of electric and hybrid vehicle technologies and their utilization [1]. However, charging requirements and driving range concerns are considered some critical barriers in a widespread use of such electric vehicles [2]. Therefore, one should keep in mind that the battery performance directly affects vehicle performance by means of range, cost, fuel economy and power for acceleration [3].

Electric propulsion performance depends on the type of batteries used [4] and improving their life-time has significant impact on the cost reduction. These technologies have shifted towards lithium-ion batteries for energy storage because the lithium-ion battery appears to be the most commonly used battery due to its specific energy, high voltage and low self-discharge rate [5,6].

Thermal management of batteries is critical in achieving life time performance and safety of the batteries. The heat generated in a battery must be controlled in order to improve lifecycle reliability and prevent failure [7,8]. Lithium-ion batteries degrade rapidly and available discharge energy reduces if the batteries operate out of their desired temperatures [2,9,10]. A thermal management system is required in order to keep the batteries in the desired temperature range; and to reduce uneven temperature distribution [7,11,12]. In a battery pack, uneven temperature distribution could lead to electrically unbalanced modules which lower the performance of the pack and vehicle [13]. Also, thermal management is required to manage its functions in an efficient and reliable state.

Thermal modeling is analyzed in details in various papers, using different approaches such as Finite element model (FEM) [14,15] or lumped parameter model (LPM) [16,17], Linear Parameter Varying (LPV) model [18], or Partial Differential Equation (PDE) model [19]. In most of the above mentioned models, a thermal model is developed which simulates the battery temperature profile in operating conditions. This thermal model is an essential part of the BMS for decision making to act on active cooling/heating [20]. As this is an energy consuming process that negatively impacts the efficiency of battery, it is crucial to provide suitable and capable thermal management to prevent any potential issues [21].

In this paper, both experimental and theoretical studies are undertaken to investigate the temperature variations of lithium-ion batteries at different charge and discharge rates of 1/2C, 1C, 2C and 2.5C. A simplified model is also developed to study temperature distribution.

2. Experimental apparatus and procedure

An experimental setup is conducted with a battery cycler used for charging/discharging of the cells under constant current, a safety cabin (Fig. 1), a data recorder and K-Type thermocouples. Cells are placed in a portable security cabin as shown in Fig. 1. The electrical connection is provided directly to battery cycler. Thermal measurements are recorded by a 10 channel data recorder. Battery is charged by C/2 and discharged at C/2, C, 2C and 2.5C current values. Nominal values are given as 10 A and 3.2 V. Cutoff voltage for the discharge is 2.3 V and for charge is 3.65 V as provided by manufacturer.

For battery surface temperature measurements, three K-type thermocouples are used. The overall sensitivity is 0.01 °C. They are attached

☆ Communicated by W.J. Minkowycz

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.03.009
0735-1933/© 2016 Published by Elsevier Ltd.

Fig. 1. Portable security cabin used.

to the surface and average of the three thermocouple measurement is used In order to evaluate the impact of the discharge rates, six experiments were performed with C/2 charge rate and C/2, C, 2C, and 2.5C constant discharge rates at an ambient condition (24 °C). In all tests the discharge was continued until the cut-off voltage of 2.3 V was reached.

3. Analysis

3.1. Heat generation

There are two main sources for the heat generation in a battery, namely Joule's heating (or Ohmic heating) and the entropy change due to electrochemical reactions [9,22,23]. The heat can be endothermic during charge and exothermic during discharge, depending on the electrode chemistry. The heat generation in battery is provided [24] as the following formula:

$$\dot{q} = -E - R + M + P. \tag{1}$$

In this formula; the E is electrical power generated by current flow and is given as;

$$E = IV \tag{2}$$

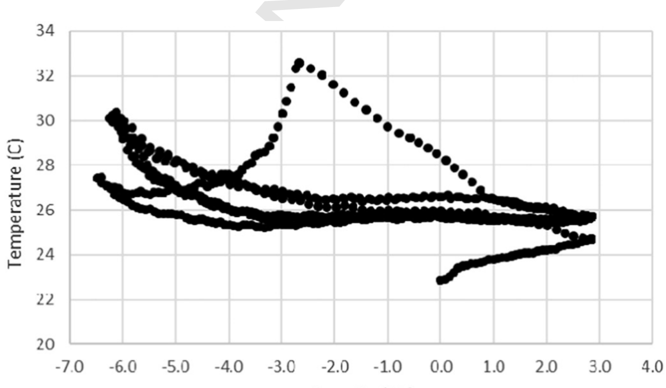

Fig. 2. Battery temperature profile during charge and discharge tests.

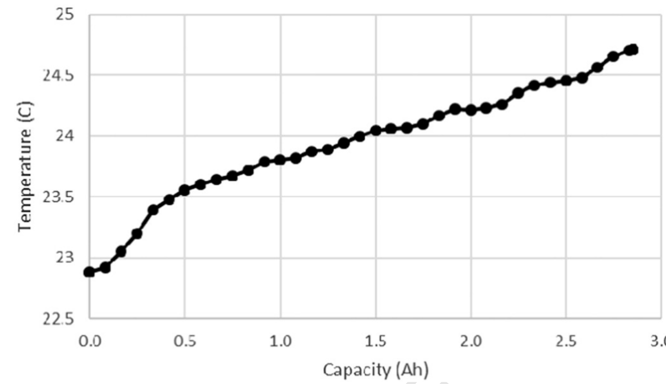

Fig. 3. Temperature change depending capacity during C/2 charge.

where R is used for reversible or entropic heat of the (i) reactions that take place in the cells and is given as;

$$R = \sum_i I_i T^2 \frac{d \frac{V_{i,avg}}{T}}{dT}. \tag{3}$$

Here, M is used to show the heat produced by non-uniform reaction rates throughout the battery and is called as the mixing heat and is given as;

$$M = \sum_j \frac{d}{dt} \int_{v_j} \sum_i c_{i,j} RT^2 \frac{\partial}{\partial t} \ln\left(\frac{\gamma_{i,j}}{\gamma_{i,j}^{avg}}\right) dv_j. \tag{4}$$

In general formula, P is used for the heat generated by material phase changes and is given as;

$$P = \sum_{i,j \neq m} \sum_i \left[\left(\Delta H^0_{i,j \to m} - RT^2 \frac{d}{dt} \ln \frac{\gamma_{i,j}}{\gamma_{i,j}^{avg}} \right) \frac{dn_{i,j}}{dt} \right]. \tag{5}$$

As seen, processing the general energy balance formula will consume high processing power and is not useful in engineering applications especially for real time processing. A close approximation can be enough and still be efficient for determining the battery temperature, depending on battery loads. Also, while providing a general approximation, a model that does not depend on the battery chemistry will be required for engineering applications. For this work, regarding the

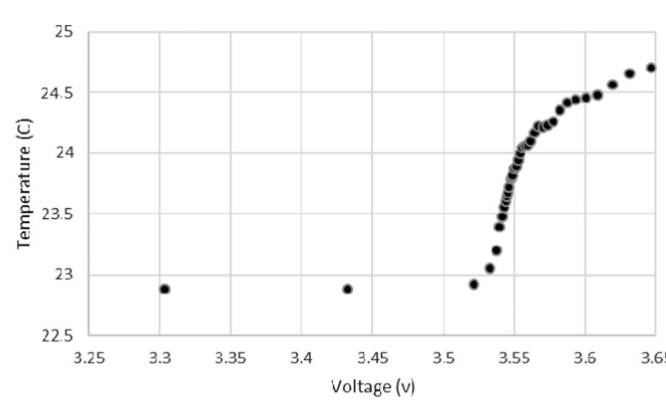

Fig. 4. Temperature and voltage change during C/2 charge.

Please cite this article as: M. Yildiz, et al., Modeling and validation of temperature changes in a pouch lithium-ion battery at various discharge rates, Int. Commun. Heat Mass Transf. (2016), http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.03.009