Applied Energy 131 (2014) 97–107

Contents lists available at ScienceDirect

Applied Energy

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

Electro-thermal analysis and integration issues of lithium ion battery for electric vehicles

L.H. Saw, Y. Ye, A.A.O. Tay *

Department of Mechanical Engineering, Faculty of Engineering, National University of Singapore, 117576 Singapore, Singapore

HIGHLIGHTS

- We modeled the electrical and thermal behavior of the Li-ion battery.
- We validated the simulation results with experimental studies.
- We compared the thermal performance of different size of cylindrical cells.
- We investigated the integration issues of cylindrical cells into battery pack.

ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form 9 May 2014
Accepted 13 June 2014

Keywords:
Battery temperature
Electric vehicles
Lithium iron phosphate
Cell integration
Battery model

ABSTRACT

Electrical and thermal characteristics of lithium-ion battery packs in electric vehicles in different operating conditions are important in order to design the battery pack thermal management system. In this work, electrical and thermal behaviors of different size of $LiFePO_4$ cylindrical cells are investigated under various operating conditions. The simulation results show good agreement with the experimental data under various operating modes. Due to the large thermal resistance of layered active material in a Li-ion cell, the temperature difference in the radial direction is significantly correlated with a diameter of cell and I_t-rates. Compared with natural convection, strong forced convection will reduce the temperature uniformity in the cell and accelerate the thermal aging rate. Lastly, integration issues of the cells into a battery pack are discussed from mechanical, electrical, thermal, control and monitoring, manufacturing and maintenance aspects. These issues could impact the performance, cost, driving range and life cycle of the battery pack in electric vehicles.

1. Introduction

Li-ion batteries are rechargeable batteries which are gaining popularity for Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) applications. Li-ion batteries with high energy density, low maintenance, less toxic, good cycle life and capable of accepting high charging rate is suitable for energy storage system in EVs and HEVs. Moreover, Li-ion batteries have no memory effect, do not required periodic deliberate full discharge and the self-discharge rate is less than half of Nickel Cadmium (NiCd) and Nickel Metal Hydride (NiMH) batteries. Hence, Li-ion batteries have been extensively investigated for potential applications in EVs and HEVs to replace NiMH and lead acid battery which have low energy density and depth of discharge. Recently, a series of fire accidents involving Li-ion battery pack in EVs indicated that there are still many challenges to be overcome, especially thermal issues of Li-ion battery. Li-ion battery needs to operate between 25 °C–40 °C to maximize its performance, cycle life and reduce capacity fading caused by thermal aging [1]. Cycle life and capacity of the Li-ion battery are inverse proportional to the temperature of the cell [2,3]. In order to satisfy the power requirements for specific devices, Li-ion batteries are electrically connected in series and or parallel to form a pack. Therefore, the uniformity of the cell temperature in the large pack should be maintained as homogeneous as possible (3–5 °C) to ensure comparable power performance, effective cell balancing and charge acceptance during regenerative braking [4]. Therefore, an accurate battery model is needed in order to predict the temperature of the battery pack when the physical battery testing facility is not available. Battery model has several advantages such as estimation of electrical and thermal behavior under different driving conditions in a short time, reduce the product life cycle cost of the battery pack and testing equipment cost [5]. The battery model is particularly useful for battery pack thermal management system and battery pack control and monitoring design and planning.

* Corresponding author. Tel.: +65 65162207; fax: +65 67791459.
E-mail address: mpetayao@nus.edu.sg (A.A.O. Tay).

http://dx.doi.org/10.1016/j.apenergy.2014.06.016
0306-2619/

Nomenclature

A	exponential voltage, V
A_s	external surface area of the cell, m^2
A_{mf}	cross section flow area for cooling air per module, m^2
A_{ms}	total module surface area exposed to cooling air, m^2
B	exponential zone time constant, $(Ah)^{-1}$
CFM	Cubic feet per minute
C_p	specific heat capacity of the battery, J kg^{-1} K^{-1}
C_{bp}	theoretical capacity of the battery, Ah
E	emissivity
E_0	battery constant voltage, V
h	convective heat transfer coefficient, W m^{-2} K^{-1}
I_t	discharge current in amperes during 1 h discharge
i	battery current, A
i^*	filtered current, A
K	polarization constant, $V(Ah)^{-1}$ or polarization resistance, Ω
λ	conductive heat transfer coefficient
$\dot{m}$	mass flow rate of air, kgs^{-1}
Q	battery capacity, Ah
R_{int}	internal resistance, Ω
R_c	terminal contact resistance, Ω
T	temperature of battery, K
T_∞	free stream temperature of air, K
t	time, s
V_{batt}	battery voltage, V
ρ	density of the battery, kg m^{-3}
ρ_{air}	density of the air, kg m^{-3}
σ_{sb}	Stefan–Boltzmann constant, W m^{-2} K^{-4}

Subscripts

exp	exponential
nom	nominal
full	fully charged
max	maximum
forced	forced convection

Superscript

k	Peukert constant

Several Li-ion battery models have been proposed to predict the charging and discharging behavior, state of charge (SOC), chemical reaction, Li-ion distribution, current density distribution, heat generation, temperature distribution, etc. Li-ion battery models can be distinguished into two major groups, mechanistic models – electrochemical, thermal models and empirical models- equivalent circuit models. Electrochemical modeling [6–10] used a coupled time variant spatial partial differential equations to model the electrochemical reaction of the battery. Although electrochemical models can accurately predict the aging and thermal behavior of Li-ion battery, the equations itself are complex and require extensive computational resources [11]. Moreover, most of the studies only presented results of numerical simulations and did not validate with experimental work [12–15].

The electrical model [16–27] or equivalent electric circuit consists of the voltage source, resistors and capacitors or set of empirical equations to represent the electrical behavior of a battery. The open circuit voltage of the battery is defined as a function of the SOC. The parameters required for the model are extracted from the Hybrid Pulse Power Characterization test (HPPC), pulse discharging or low I_t-rate of constant current discharging curves. These models are easy to use and required shorter computational times and have an advantage in large system simulations, especially in analyzing dynamic and thermal behavior of the battery under different driving cycles.

Lithium iron phosphate (LFP) battery have high thermal runaway temperature (270 °C), non-toxic, do not release oxygen at elevated temperatures and high cycle life (1000–2000) as compared to $LiCoO_2$, $LiMnO_4$ and $LiNiMnCoO_2$ has make it become an attractive solution for future EVs battery pack [28]. Although there are some studies have been carried out to investigate the thermal behavior of Li-ion battery under different driving cycles, modeling work on LFP cell are rare [20,29–31].

Li-ion batteries can be constructed into various shapes and sizes for different applications: spiral wound to form cylindrical cells or stacked plates to form pouch cells. The fabrication technology of spiral wound design of the Li-ion battery is more mature and commonly found in the market. Besides, spiral wound design has several advantages as compared to prismatic and pouch cell design such as: easy to fabricate, high energy density, mechanical stability, incorporated safety vent and not prone to swelling during operation [32]. However, small specific area to volume of a cylindrical battery could lead to the development of a large temperature gradient in the cell and thermal aging issues, heat is retained in the cell and hot spots are formed in the center of the cell. Large temperature gradient developed across the cell at large load could cause capacity fading [33]. The temperature gradient in the cell is significantly correlated with the diameter of the cell and I_t-rates. This implies that thermal analysis of different sizes of cylindrical cell is necessary to provide a guideline for determining a suitable size to integrate into EVs or HEVs battery pack.

In the present work, an electrical–thermal battery model was developed to investigate the electrical performance and thermal behavior of two different sizes of spiral wound LFP cell. The simulation results are confirmed by experimental data. The development of internal temperature under different cooling conditions was predicted by the battery model. Next, the validated single cell model is then extended to the whole battery pack to examine the thermal response of the cell under US06 Supplemental Federal Test Procedure (SFTP) driving cycle. Furthermore, the integration issues of the cell into the battery pack are discussed from different points of view, such as mechanical, electrical, thermal, manufacturing and maintenance. This study will serve as a basic guideline for cell thermal management system design and integration of cell for EVs and HEVs battery pack.

2. Model development

2.1. Battery model

A battery model is needed to describe the correlation between the input parameters to the Li-ion battery such as current or power and outputs of the battery model like voltage, SOC for constant current charging/discharging and dynamic conditions. The modified Shepherd model was used to model the voltage dynamics of the LFP cell in this study [34–36]. Eqs. (1) and (2) are used to model the charging and discharging characteristics of the battery respectively [35,36]. In this model, the internal resistance of the cell was assumed to be constant and does not change with SOC and temperature. Moreover, the battery model was treated as independent of the temperature and the model parameters for charging and discharging are identical and the hysteresis phenomenon was not