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Electro-thermal analysis of Lithium Iron Phosphate battery for electric vehicles

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HIGHLIGHTS

- We modeled the electrical and thermal behavior of the Li-ion battery.
- We analyzed the dynamic behavior of the cell using SFUDS cycle.
- We carried out experimental study to validate the simulation results.
- We studied the thermal response of the battery pack under different driving cycle.
- Heat generation of the battery pack is the highest for US06 cycle.

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ABSTRACT

Lithium ion batteries offer an attractive solution for powering electric vehicles due to their relatively high specific energy and specific power, however, the temperature of the batteries greatly affects their performance as well as cycle life. In this work, an empirical equation characterizing the battery's electrical behavior is coupled with a lumped thermal model to analyze the electrical and thermal behavior of the 18650 Lithium Iron Phosphate cell. Under constant current discharging mode, the cell temperature increases with increasing charge/discharge rates. The dynamic behavior of the battery is also analyzed under a Simplified Federal Urban Driving Schedule and it is found that heat generated from the battery during this cycle is negligible. Simulation results are validated with experimental data. The validated single cell model is then extended to study the dynamic behavior of an electric vehicle battery pack. The modeling results predict that more heat is generated on an aggressive US06 driving cycle as compared to UDDS and HWFET cycle. An extensive thermal management system is needed for the electric vehicle battery pack especially during aggressive driving conditions to ensure that the cells are maintained within the desirable operating limits and temperature uniformity is achieved between the cells.

1. Introduction

The world relies heavily on fossil fuel to meet the daily power demands, ranging from electricity generation to transportation. In 2009, the logistics sector had contributed to 61.7% of the total world oil consumption and 23% of the total world CO_2 emission [1]. With advances in battery technology, concerns on global warming and increasing fuel prices, automotive manufacturers are forced to shift their attention to electric vehicles (EVs). EVs are more energy efficient and cleaner than conventional Internal Combustion Engine (ICE) vehicles and are projected as the most sustainable solutions for the future transport [1–3], however, the success of EVs depends on the development of the battery.

Lithium-ion batteries provide an attractive solution for EVs due to its high power and energy density, however, thermal issues in Li-ion batteries have to be addressed to make them safer, reliable and last longer for high power applications. Bandhaeur et al. [4] have provided a detailed review of the thermal issues in Li-ion batteries. Safety, cycle life and capacity retention are some of the major aspects affected by the operating temperature. Hence, a control and management of the thermal envelope is required to have a safer and reliable operation of a Li-ion battery.

Various test procedures used to investigate the performance, reliability and safety of Li-ion batteries are documented in ISO 12405-1/2, IEC 62660-1/2 [3]. In order to design a realistic thermal management system for EVs, it is also important to characterize the

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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)$^{-1}$
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	constant voltage, V
h	convective heat transfer coefficient, W m^{-2} K^{-1}
I_{dis}	discharge current, A
i	current, A
i^*	filtered current, A
K	polarization constant, V(Ah)$^{-1}$ or polarization resistance, Ω
$\dot{m}$	mass flow rate of air, kg s^{-1}
Q	capacity, Ah
R	internal resistance, Ω
R_c	terminal contact resistance, Ω
T_{dis}	discharge time, h
T_{module}	module temperature, K
T_{surf}	surface temperature of battery, K
T_∞	free stream temperature of air, K
t	time, s
V_{batt}	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}

Subscript

exp	exponential
nom	nominal
full	fully charged
max	maximum

Superscripts

k	Peukert constant

thermal phenomena of Li-ion cell for the required transient power response. Among the various driving cycles, Simplified Federal Urban Driving Schedule (SFUDS) has been widely used to evaluate the power delivery capability and cycle life of the cell at laboratory level [5–7], however, the facility needed to carry out the testing of the EV battery packs such as high power programmable battery cycler is always expensive and requires several hundred hours of testing. The battery pack may not be comprehensively tested due to the limitations of the battery cycler.

Numerical modeling could be used to overcome the limitations in battery testing. Numerical modeling not only helps to improve the understanding of the battery operating mechanism but also provides internal information that are difficult to obtain through experiments such as electrochemical reaction rates inside the cell, heat generation, temperature distribution, voltage distribution, current distribution, etc. Various mathematical models have been used to investigate the thermal response of the battery such as empirical equations [7], electrochemical models [8–12], RC models [13–15], and lumped parameter models [16,17]. Although electrochemical models can predict the aging and thermal behavior of the Li-ion battery, coupled time variant spatial partial differential equations make them complex and their solution demands extensive computational resources [18]. Besides, most of the studies only presented a numerical simulation results and doesn't compare with the experimental work [4,19–22]. Various types of thermal management systems such as air cooling [23–25], liquid cooling [26,27] and phase change material [28–30] technologies have been proposed to maintain the batteries at the optimum operating temperature at both cell and pack levels [31].

In view of the challenges in experimental testing and detailed modeling, the objective of this work is twofold. First, an empirical equation coupled with a lumped thermal model has been used to predict the cell voltage, heat generation, temperature rise of the cell during constant-current discharging and SFUDS cycle for an 18650 Lithium Iron Phosphate (LFP) cell and is validated with experiments; and second, to apply the validated single cell model to investigate the thermal response of the battery pack of a converted EV under Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Driving Schedule (HWFET) and US06 Supplemental Federal Test Procedure (SFTP) driving cycles. The results are discussed in terms of the total heat generated during these driving cycles and the evolution of the battery pack temperature under a forced convection cooling system.

2. Mathematical model

2.1. The battery model

A battery model is needed to define its voltage in terms of current and state of charge (SOC). In this study, modified Shepherd model has been employed to represent the voltage dynamics of the LFP cell [32–34]. A typical discharge curve of the Li-ion battery is shown in Fig. 2. The discharge curve of the Li-ion battery can be divided into three sections. The first section represents the exponential potential drop of the cell during initial discharge. The second section represents the amount of charge that can be extracted from the cell before reaching the nominal voltage of the cell. The last section represents the total discharge of the cell, when the voltage of the cell drops rapidly to the cut off voltage. The modified Shepherd equation for charging and discharging is given by Eqs. (1) and (2) respectively [32–34]. It is assumed that the internal resistance of the cell is constant throughout the charging and discharging cycle and doesn't change with the I_t-rates. The temperature effect on the battery model behavior is neglected and the model parameters for discharging and charging are identical.

Charging ($i^* < 0$)

$$V_{batt} = E_0 - R\cdot i - K\frac{Q}{it - 0.1\cdot Q}\cdot i^* - K\left(\frac{Q}{Q - it}\right)it + A\exp(-B\cdot it) \tag{1}$$

Discharging ($i^* > 0$)

$$V_{batt} = E_0 - R\cdot i - K\frac{Q}{Q - it}\cdot i^* - K\left(\frac{Q}{Q - it}\right)it + A\exp(-B\cdot it) \tag{2}$$

The voltage of the cell at a fully charged state is defined in Eq. (3) [33,34].

$$V_{full} = E_0 - R\cdot i + A \tag{3}$$

The voltage at the exponential section is defined in Eq. (4) [33,34].