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Development of an Advanced Two-Dimensional Thermal Model for Large size Lithium-ion Pouch Cells☆

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ABSTRACT

In this work, a LiFePO4/graphite lithium-ion pouch cell with a rated capacity of 45Ah has been used and a two dimensional thermal model is developed to predict the cell temperature distribution over the surface of the battery, this model requires less input parameters and still has high accuracy.

The used input parameters are the heat generation and thermal properties. The ANSYS FLUENT software has been used to solve the models. In addition, a new estimation tool has been developed for estimation of the thermal model parameters. Furthermore, the thermal behavior of the proposed battery has been investigated at different environmental conditions as well as during the abuse conditions. Thermal runaway is investigated in depth by the model.

1. Introduction

Under the pressure of rising petroleum prices, the increase of global energy consumption and also the effect of global warming, research have spurred into the development of various types of clean energy transportation systems such as Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs) and Plug-In Hybrid Electric Vehicles (PHEVs) [1–5,25,26].

Lithium-ion batteries play an important role as energy carriers in our society mainly in HEVs, BEVs and PHEVs and have a promising future because of using less poisonous materials, and also of their lightness, high energy and power density. However, the main obstacle to its widespread application is the cost, safety and bad performance at some given temperature range. Therefore, a good battery thermal management can play a key role in optimizing its use.

Advanced research in this field induces to a wide use of large scales and capacities of lithium-ion pouch batteries in PHEVs and EVs and these formats have the advantage of reducing the number of cell in the module and pack levels. In transportation application, they are generally subjected to heavy demands such as fast charge and fast discharge resulting of the vehicle's acceleration. These solicitations increase significantly the battery temperature and may cause inhomogeneous temperature, voltage and current distributions. This phenomena leads to reduce the battery performance and lifetime: indicated mainly by capacity fade and resistance increase. Furthermore if heat transfer from the battery to the surroundings environment is not sufficient, the battery temperature can raise very fast and then the reaction rate increases and goes out of control, hence the thermal runaway can occur [6]. The thermal runaway effect is the main safety problem of lithium ion battery and can cause fire and explosion due to the battery overheating or short-circuit.

In order to keep the battery temperature on the safe range on one hand and to increase its performance on other hand, the knowledge of the battery temperature distribution is necessary. Therefore a good use of batteries increases its lifetime.

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In the field of thermal modeling, two types of techniques have been considered in the literature:

- Analytical techniques give continuous solutions and can show explicitly how the parameters affect the solutions [8]. Nevertheless, these techniques are only applicable for simplified cases [7], for example in the case of lumped-parameters approach where the battery surface temperature is considered as uniform or the Biot number is lower than 1 [9]. Several analytical techniques exist such as Laplace transformation, separation of variables, Green's function, etc.. . .
- Numerical techniques are performed on complex models depending on the design and the multidirectional heat transfer of the battery. They use many discretization techniques such as finite differential method (FDM) [23], finite volume method (FVM), the finite element method (FEM) [14,18] and etc. . .; to solve the energy balance equation.

Numerical methods are usually implemented in Commercial software packages such as ANSYS Fluent, COMSOL Multiphysics, etc. . . Generally, these models are of high importance for dimensioning of the cooling [29] and heating systems, also for analyzing large scale or complex design battery including battery holder and electrode tabs. Despite its good accuracy, the implementation of CFD models requires an immense effort on meshing and time computation. While lumped-parameters methods are well fitted for battery with simple design, small size and uniform surface temperature [13,22].

Heat generation can be considered as the main parameter for calculation in thermal modeling. It can be determined by using the experimental test [10,14,16,21] or electrochemical models [15,17]. The first approach is an approximation that allows an easier mathematical solution. However, the second approach gives more accurate solution by solving the mass and energy balances simultaneously, so it requires an immense computational effort.

Many numerical methods were developed in the literature to predict the transient response of the temperature distribution. Inui et al. developed two-dimensional and three-dimensional simulation models of the transient response of the temperature distribution in a small cylindrical as well as in a prismatic lithium ion battery during a discharge cycle [10]. In Inui's model, the heat generation is calculated based on experimental tests. Kim et al. and Guo et al. developed a three-dimensional thermal finite element modeling of cylindrical lithium-ion battery for analyzing the temperature distribution under thermal abuse application [14,15]. This model considers also the geometrical features to simulate the thermal behavior in different conditions. In Kim's model, the heat generation originated from lithium ion battery component reactions, while as Guo's model heat generation is based on experimental test.

In this work, a LiFePO4/graphite lithium-ion pouch cell with a rated capacity of 45Ah has been used and a two dimensional thermal model is developed to predict the cell temperature distribution over the surface of the battery, this model requires less input parameters and still has high accuracy. The used input parameters are the heat generation and thermal properties. The ANSYS FLUENT software has been used to solve the models. In addition, a new estimation tool has been developed for estimation of the thermal model parameters at each direction of the cell. Furthermore, the thermal behavior of the proposed battery has been investigated at different environmental conditions as well as during the abuse conditions. Thermal runaway is also investigated in order to predict it in advance.

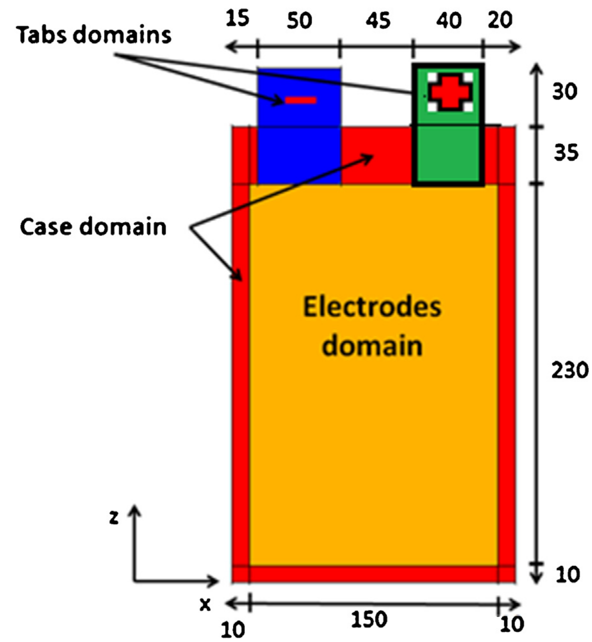

Fig. 1. Schematic diagram and dimension (mm) of pouch Li-ion battery.

2. Thermal modeling

Taking into account the small thickness (13 mm) of the $LiFePO_4$/graphite lithium-ion pouch cell, the heat development in the y-direction has been neglected. Thus a two-dimensional transient model has been used. As shown in Fig. 1, the size and different domains (Tabs, case and electrode domains) of the battery are illustrated. These domains are made by different materials. A transient heat conduction equation is sufficient to describe thermal phenomena in the battery and the convective term inside the battery (electrode-electrolyte) can generally be neglected [9]. In this study the active material of the battery is assumed to consist of several cells layers. Therefore, the thermal conductivities are anisotropic in the thermal model, with a higher value along x and z-directions, than the normal direction to the layers. Furthermore the thermal conductivity along x-direction is the same than the z-direction. Therefore an equivalent material is set up to model all different materials that consists the battery cell. The radiative and convective heat transfer from battery surface to the surrounding is also taking into account.

Based on the above assumption, the energy balance equation over a representative elementary volume (REV) in a battery, enable to predict the transient response of the temperature distribution for the 2D thermal modeling is formulated as:

In the electrode and tabs domains:

$$k\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2}\right]+q_g=\rho.C_p\frac{\partial T}{\partial t} \quad (1)$$

For the electrodes domain, the heat generation is given by:

$$q_g=\frac{1}{V_{bat}}\left[RI^2+\left(T\left[\frac{dE}{dT}\right]\right)I\right] \quad (2)$$

For the Tab domain, the heat generation is given by:

$$q_g=\frac{R'I^2}{V_{tab}};R'=\rho'\frac{l}{S} \quad (3)$$

In case domains

$$k\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2}\right]=\rho.C_p\frac{\partial T}{\partial t} \quad (4)$$