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Streamline three-dimensional thermal model of a lithium titanate pouch cell battery in extreme temperature conditions with module simulation

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HIGHLIGHTS

- We present the development of 3D thermal model for high-power battery (LTO).
- A 3D simplification of the thermal model couplings can reduce computation time.
- The influence of extreme temperatures on lithium-ion batteries is discussed.

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ABSTRACT

In this paper, the development of a three-dimensional (3D) lithium titanium oxide (LTO) pouch cell is presented to first better comprehend its thermal behavior within electrified vehicle applications, but also to propose a strong modeling base for future thermal management system. Current 3D-thermal models are based on electrochemical reactions which are in need for elaborated meshing effort and long computational time. There lacks a fast electro-thermal model which can capture voltage, current and thermal distribution variation during the whole process. The proposed thermal model is a reduce-effort temperature simulation approach involving a 0D-electrical model accommodating a 3D-thermal model to exclude electrochemical processes. The thermal model is based on heat-transfer theory and its temperature distribution prediction incorporates internal conduction and heat generation effect as well as convection. In addition, experimental tests are conducted to validate the model. Results show that both the heat dissipation rate and surface temperature uniformity data are in agreement with simulation results, which satisfies the application requirements for electrified vehicles. Additionally, a LTO battery pack sizing and modeling is also designed, applied and displays a non-uniformity of the cells under driving operation. Ultimately, the model will serve as a basis for the future development of a thermal strategy for LTO cells that operate in a large temperature range, which is a strong contribution to the existing body of scientific literature.

1. Introduction

Lithium-ion batteries (LiBs), which have been proven to be the ideal power source for electric vehicles (EVs) and hybrid electric vehicles (HEVs), strike the best balance between power/energy density and costs for energy storage [1,2]. However, several obstacles limit the market integration of the LiB in the HEVs/EVs applications such as their safety cost issues [3], recycling issues [4], charging infrastructure [5], charging time [6], etc.

In addition, as safety behaviors and a longer life-cycle of the batteries demand a narrow temperature range, battery temperature remains one of its most essential operating parameters [1,7]. At high temperatures, LiBs undergo thermal runaway, which

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generates fatigue damage of the battery as a consequence [8,9]. While at low temperatures, the battery cell has a reduced power and energy capability due to its increasing internal resistance and decreasing cell capacity [10–12]. Therefore, thermal stability is a major concern for LiBs safety and performance.

Nowadays, different Li-ion technologies distinguish themselves within HEV and EV applications in terms of energy density, lifetime and low costs [13,14]. Lithium titanate battery is one kind of lithium-ion battery, with LTO for anode material, that has been attracting more and more attention because of its excellent thermal stability [15–18]. As reported in Ref. [17], in large-format lithium-ion batteries for EV/HEV applications, the integration of LTO-based cells in a battery pack could be seen as an interesting asset because of their thermal stability that could prevent safety hazards while driving. Moreover, Wang et al. [19] studied the thermal behavior of LTO cells and confirmed the acknowledgeable embarked energy and strong thermal stabilities of the lithium-titanate batteries. Although LTO thermal behaviour has been studied by published investigations, the reported studies mainly address the thermal behavior. There lacks a comprehensive and wide electro-thermal modelling. In addition, the reported studies have been only done at room temperature, thus, studies on LTO cells at extreme temperatures been rarely documented. Therefore, in this paper, the development of thermal management system for LTO cells is proposed. Our objective is to establish an effective heat-diffusion method that allows LTO cells to operate within a certain temperature range and to have an even temperature distribution on their surface for low and high temperatures.

However, since this goal is related to thermal effects of the battery system, a proper way to establish this battery thermal management strategy starts with the development of a thorough battery model. There exists a number of battery thermal models with different modeling approaches, going from electrochemical models [20–23] which are very accurate but computationally demanding, to electro-thermal models based on equivalent circuit models which are fast but easy-going [24–28]. However, a model combining fast response with an adequate accuracy especially for thermal behavior and simplicity are difficult to find. Du et al. [29] proposed an alternative model involving a 3D-thermal model with a 1D-electrochemical model considering only one layer which reduces the computational time. This joined-modeling technique has been already approved in literature [22]. Yet, with this approach, in-depth parameters (size of the electrode, conductivity, etc.) and complex equations (Poisson's law) are required to function the model such as: size of the electrode, conductivity, etc. Since it is difficult to acquire those parameters experimentally, in this paper, an alternate and simplified version of the model is proposed. Instead of a electrochemical approach, a 0D-electrical model is coupled with a 3D-thermal model. In this context, the modelling approach will allow less needed invasive parameters and a faster computational time, for which thermal automotive applications are demanding. Moreover, studies reporting the development of thermal models based on this approach for LTO are lacking in the current literature, providing then a strong contribution.

Consequently, the aim of this paper is to develop a LTO thermal model able to address the thermal accuracy issues properly. To ensure a pragmatic thermal representation of the battery, we employ an extensive three-dimensional (3D) modeling approach. To reduce the computational time in order to produce a competitive modeling structure, as explained above, the 3D model is combined with a simplified electrical model for calculating its heat generation rate.

Additionally, the model is trained with data from test matrices that consist of two extreme temperatures, 10°C and 45°C, in order to extend the range of the model; high and low temperature effects are crucial factors to consider in the context of battery thermal management. Moreover, negative temperature test at −15°C was also performed but due to the recommendation of the thermal camera manufacturer, solely a thermocouple was used instead for the validation part.

Alternatively, after the validation of the 3D thermal model of the LTO battery, we proposed to upscale the model to a battery pack. In automotive application, thermal management of multiple cell in series and/or in parallel is indeed crucial. The simulation results will provide feedbacks regarding the efficiency of the modeling methodology developed herein and the temperature gradients in a battery pack.

The paper is organized in such a way that Section 2 describes the model development, Section 3 deals with the experimental protocol for parameter assessment, Section 4 illustrates the simulation results and model validation, Section 5 presents the studies on performance of a LTO-battery pack, and finally, conclusions are given in Section 6.

2. Model development

2.1. Pouch-cell geometry

In this study, a 3D-thermal model is developed for a LTO-based cell. Fig. 1 presents the schematic of the lithium-ion pouch cell. As it is currently well-known, the battery is composed of several layers, containing a negative current collector (CC), negative electrode, separator, positive electrode and positive CC). However, a model that considers all the layers included in a pouch cell requires a long computational time due to the meshing effort. A modeling approach using a single pair of layers has been already reported in the literature to describe the thermal behavior of Li-ion cells 23 [30], a description is shown by Fig. 1a. Nonetheless, in-depth parameters are still required to function the model. Therefore, to further simplify the model, as shown by Fig. 1b, a equivalent single flat core with a positive and negative tabs is assumed to be designed as a layered stack for the thermal-modeling approach.

2.2. Description of the model

As shown in Fig. 2, a 3D-thermal model of a lithium-ion cell is built, which treats the battery as a core with two tabs. It is an effective method to couple a 1D electrochemical with a 3D thermal model to study cells temperature and voltage characteristics [31], [22]. However, as it was reported in Ref. [31], lots a parameters are required to operate the electrochemical model, and some of them require invasive and expensive techniques to be obtained, such as the length of the electrode or the diffusivity coefficient. In addition, a thermal behavior model is essentially an energy conservation equation in each representative elemental volume of the cell at any given time interval, i.e, the sum of the absorbed and generated heat equals the sum of the lost heat and the increased internal energy inside the micro unit. Therefore, a key requirement for the accuracy of a 3D thermal modeling is to obtain the generated heat flowing inside the pouch cell.

2.3. Electrical modeling

As explained before, the modeling of the complete pouch cell has been reduced to one core only as a mean to reduce the meshing effort. An electrical model based on the equivalent circuit modeling (ECM) approach is used instead of an electrochemical model to assess the heat generation estimation [32–34]. Fig. 3 depicts the proposed ECM. The model is a 2nd-order Thevenin model with a bi-