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Thermal modeling of large prismatic $LiFePO_4$/graphite battery. Coupled thermal and heat generation models for characterization and simulation

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HIGHLIGHTS

- Thermal modeling of a large prismatic $LiFePO_4$/graphite battery.
- Experimental determination of the interfacial thermal resistance between the battery and its cooling system.
- Heat generation modeling including electrical losses and entropic heat.
- Method for electrical parameters determination, considering the cell heating during characterization.

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ABSTRACT

This paper deals with the thermal modeling of a large prismatic Li-ion battery ($LiFePO_4$/graphite). A lumped model representing the main thermal phenomena in the cell, in and outside the casing, is hereby proposed. Most of the parameters are determined analytically using physical and geometrical properties. The heat capacity, the internal and the interfacial thermal resistances between the battery and its cooling system are experimentally identified. On the other hand, the heat sources modeling is considered to be one of the most difficult task. In order to overcome this problem, a heat generation model is included. More specifically, the electrical losses are computed thanks to an electrical model which is represented by an equivalent electric circuit. A method is also proposed for parameter determination which is based on a quasi-steady state assumption. It also takes into account the battery heating during characterization which is the temperature variation due to heat generation during current pulses. This temperature variation is estimated thanks to the coupled thermal and heat generation models. The electrical parameters are determined as function of state of charge (SoC), temperature and current. Finally, the proposed coupled models are experimentally validated with a precision of 1 °C.

1. Introduction

Energy management and security are key issues for electric and hybrid vehicles development. Many battery sizing criteria are linked to its thermal behavior (power requirement, autonomy, temperature limitations, life span). Thus, a thermal model is useful when it comes to battery and its cooling system optimization. During operation, Battery Management Systems (BMS) ensures the efficiency and the safety of the energy storage. By means of a thermal model, the BMS is able to estimate the internal temperature and to predict its evolution. Besides, this information can improve the accuracy of an electrical model, used to monitor the state of charge (SoC) or the state of health (SoH) [1,2].

Several papers deal with the thermal modeling of battery, using different approaches such as Partial Differential Equation (PDE) [3] or Linear Parameter-Varying (LPV) models [4], finite element method (FEM) [5–7] or electrical equivalent circuit [8,9]. Thermal parameters can be determined using analytical relations which need a previous knowledge of the battery [6,10]. They can also be determined experimentally by adapting a model to experimental data [11–13].

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The purpose of this work is to establish a model suitable for the on-board energy management of a battery pack. 3D thermal models (such as FEM) are well-suited for the battery design purpose, but they are not compatible with the low computational resources of micro-controllers used in BMS [5,14]. Therefore, a thermal model of a large prismatic Li-ion battery ($LiFePO_4$/graphite) is proposed, based on an equivalent electrical circuit where the thermal parameters are determined using analytical and experimental methods.

Inside a prismatic battery pack, cell temperatures have been measured as quite homogeneous. The hottest elements appeared to be in the central location, making this position critical for life span and reliability. Consequently, this study focuses on modeling the battery pack central cell (40 Ah). A difference of about 0.2 °C has been measured between the latter and the neighboring cells. Since this thermal gradient is small, the central cell is assumed to expel its heat only through its base (see Fig. 1). As a result, their cooling performances are strongly dependent on the interfacial thermal resistance between the base and the cooling system. This thermal resistance has to be determined experimentally, but as it has no thickness, it cannot be measured using sensors. Therefore, it has to be determined indirectly.

For any battery thermal model, the heat sources are one of the most difficult components to represent, since they are highly non linear. Thus, a specific model is developed for heat generation, which computes both entropic heat and electrical losses, in relation to the inner temperature determined by the thermal model (Fig. 2).

The entropic heat is usually modeled by means of an entropy-variation look-up table expressed as a function of the SoC. Its measurement is time-consuming, as the classical method requires approximately one day per SoC-operating point [15,16]. Hence, several days, or even weeks, are necessary to obtain a high-resolution table. Interestingly, a new method has been recently proposed by Schmidt et al. [17], taking only several hours and giving very high resolution results.

Electrical losses are extracted from an electrical model of the battery which is strongly dependent on temperature, current, SoC and aging. Hence, they present a difficult task in terms of modeling. They can be estimated by solving electrochemical equations, but the latter requires the knowledge of many internal parameters, which are difficult to obtain [18–20]. Another approach is to use

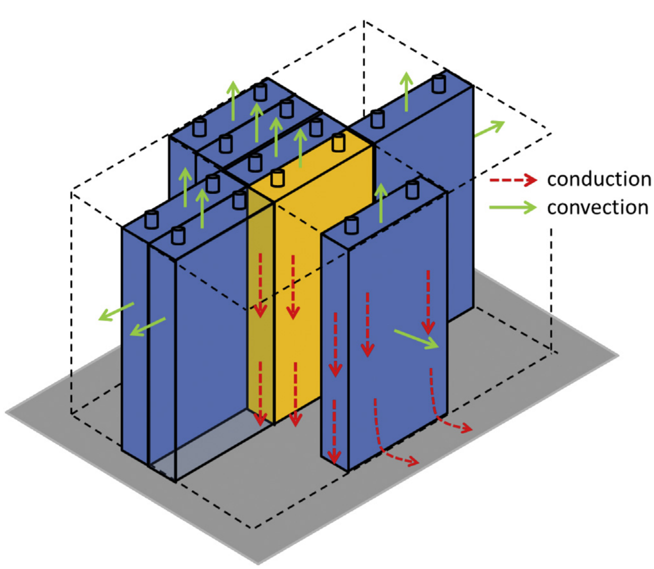

Fig. 1. Prismatic cells (3 × 7) integration in battery pack, on a cooling plate (grey). White arrows represent cooling heat flows.

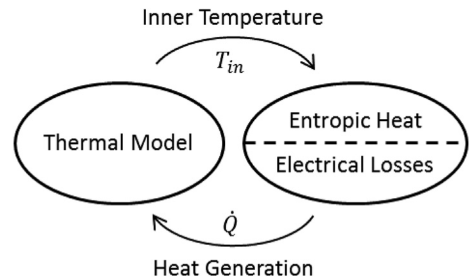

Fig. 2. Coupled thermal and heat generation models.

equivalent electrical circuits. The simplest one is a Thévenin equivalent circuit (whose single resistance eventually depends on temperature, current or SoC) [7,21]. Dynamic models are also used, similar to Randles' circuit. Many studies achieved modeling of the diffusion phenomenon, which corresponds to the mass transport within the battery electrodes and electrolyte. It occurs at low frequencies (below 1 Hz) and depends on the considered chemistry. The electrical behavior of the diffusion phenomenon can be approximated by: a series RC circuit [22–24], constant phase elements (CPE) [24,25] or non integer derivatives [26]. Moreover, the polarization (caused by a current) and the relaxation (in open-circuit) have different dynamics. Thus, a complete model should consider both case [27].

Regardless of the chosen method, any electrical model requires well-determined parameters. Their accurate determination is made difficult because of their sensibilities to SoC and temperature variations during tests, especially for low temperatures and high currents. One approach is to work in the frequency-domain, using electrochemical impedance spectroscopy (EIS) [26,28]. They can also be determined in the time-domain, through current pulses [23–25]. These two approaches can be combined in order to reach a maximum precision [28].

In this paper, another equivalent electrical circuit is being proposed in order to model the battery electrical behavior, from which losses are computed. Its parameters are functions of temperature, current and SoC (aging is not considered in this study). Because the aim of this study is to model the heat generation, only the polarization behavior is characterized. Therefore, relaxation is assumed to behave like polarization and to generate no heat. The coupled thermal and heat generation models present the benefit of being able to compute the cell key-temperatures evolution, while being simple enough to be implemented in real time calculators.

In the first part, main thermal phenomena are modeled using a thermal network. Analytical and experimental methods for thermal parameters identification are presented. In the second part, heat sources are modeled and a method is proposed for electrical parameters determination. Finally, the experimental validation of the coupled models, through a discharge–charge cycle, is presented and discussed.

2. Thermal modeling

2.1. Model structure

A lumped thermal model [10] – also called equivalent electric circuit – has been used to model the studied cell. This approach is based on the formal analogy between thermal and electrical phenomena. Nodes are associated with volumes (assumed isothermal), capacitances represent heat accumulation, resistances represent heat transfers (by conduction, convection or radiation), current sources represent heat generation and voltage sources represent