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Transient thermal analysis of a lithium-ion battery pack comparing different cooling solutions for automotive applications

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HIGHLIGHTS

- An experimental set-up is designed and developed for thermal characterization of a Li-ion battery.
- Heat generation and internal resistance profile at various C-rates (1C, 2C, 5C and 8C) are studied.
- Heat entropic coefficient and internal resistance determination with temperature dependence were performed.
- A battery thermal model is developed and used in a CFD-3D software for cooling methods analysis.

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Entropy heat coefficient
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ABSTRACT

This paper presents a computational modeling approach to characterize the internal temperature distribution within a Li-Ion battery pack. In the mathematical formulation both entropy-based and irreversible-based heat generation have been considered; combined with CFD software in order to simulate the temperature distribution and evolution in a battery pack.

A prismatic Li-ion phosphate battery is tested under constant current discharge/charge rates of 1C, 2C, 5C and 8C. Model parameters (in particular, the entropic heat coefficient and the internal resistance) needed for the calibration of the model are determined using experimentation.

The model is then used to simulate two different strategies for the thermal control of a battery pack in case of car application: an air-cooling and a liquid-cooling strategy.

The simulation has highlighted the pros and cons of the two strategies, allowing a good understanding of the needs during the process of battery pack design and production.

1. Introduction

Since the performance, life, safety and reliability of Li-Ion batteries are quite dependent on the operating temperature, great interest has been devoted to study cooling solutions and control algorithms for thermal management.

Temperature affects battery in many ways: operation of the electrochemical system, round trip efficiency, power and energy available, safety and reliability, life and life-cycle cost.

There are different approaches to study thermal behavior in the battery. These approaches can be broadly categorized into computational and experimental approaches. Detailed studies of the temperature distribution within Li-Ion battery cells during charging and discharging conditions have been proposed by several authors [1–4]. Computational approaches mostly consist of studies conducted utilizing FEM (Finite Element Method) thermal simulations and are often coupled with detailed models that characterize the electrochemical reactions and transport phenomena that take place inside a battery pack.

Such simulations are extremely useful to gain understanding on how the temperature distribution affects the performance of a battery cell. Moreover, they also provide important information for cell modeling and design; for instance, they can help in identifying hot spots. However such tools are too complex to be applied to studies oriented to the characterization of the electro-thermal performance of modules and battery packs, or to the design of battery cooling systems and control algorithms, especially developed for on-board applications due to the

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complexity of the model.

In EV/HEV applications, a thermal model that could predict battery temperature under various charging and discharging conditions is necessary for developing thermal management algorithms and cooling strategies. To achieve these objectives, the model must be both sufficiently simple to be executed quickly, and accurate enough to provide a reasonable estimation of thermal dynamics inside the cell. Computationally efficient models that can provide a reasonable estimate of the cell thermal profile can be useful tools for battery pack designers and integrators.

Experimental approaches to study thermal behavior have also been attempted. Some researchers have installed thermocouples insides the battery (or on the battery surface [5]) to measure internal temperature [6,7]. It should be noted that thermocouples inserted into cells increase manufacturing costs (especially for large battery capacity) and represent a potential safety threat. Moreover, the surface measured temperature can only describe the trends of core temperature changes rather than the real time changes because the heat conduction between the heat source and battery surface is not instantaneous [8]. This means that a thermal runaway cannot be detected only with surface temperature monitoring. For some applications, this can be critical especially with high C-Rates [9].

Hence, the core temperature estimation is not an appropriate method for industrial applications.

In these applications constructing a thermal model to predict the internal temperature with a Computational Fluid Dynamic CFD simulation is a promising approach to estimate a battery's thermal state. Ye and his team [10], designed and analyzed the thermal behavior of a cylindrical Li-ion battery pack using a computational fluid dynamic analysis to investigate the air cooling system for a 38,120 cell battery pack. The Heat generated by the cell during charging was measured using an accelerating rate calorimeter. This method provides a simple way to estimate thermal performance of the battery pack when the battery pack is large and full transient simulation is not viable.

Lin [11] designed an adaptive observer method based on a two-state thermal model to estimate the core temperature.

However, Lin's model ignored the effect of heat generation caused by entropy changes. Although this contribution is relatively small compared with the overpotential heat generation, it can influences the thermal behavior significantly. Especially, the contribution from entropy changes can be high for some battery chemistries [12]. Forgez's [13] thermal model considers the entropy change, but it lacks a quantitative analysis of the influence of heat generation.

This work aims at developing a thermal model taking into account the entropy change. This model is also used in Lin's [11], Forgez's [13] and Zhu's [5] model research works. What differs is that the entropy change is considered in the heat generation formulation through experimental tests to get the entropy coefficients, showing its influence in the CFD simulations.

Furthermore, empirical relationship between the internal resistance (the irreversible heat) and the temperature of the cells is found. Hence, the model is combined with a CFD code in order to make predictions about the cooling power needed to operate the battery pack under safety conditions.

The simulation has highlighted the pros and cons of the two strategies (air and liquid cooling), allowing a good understanding of the needs during the process of battery design and production.

These indications are now used for a re-design of the battery pack that will be tested allowing a second step of validation of the model in a subsequent paper.

2. Thermal modeling

The thermodynamic energy balance for Li-ion batteries has been discussed in detail by Bernardi et al. [14]. In the derivation of the energy balance, the temperature of the battery is assumed uniform throughout the battery and changes in temperature over time are assumed to be determined by the following processes: reactions, changes in the heat capacity of the system, phase changes, mixing, electrical work and heat transfer with the surroundings. However, not all the processes contribute equally to the heat generation within the cell.

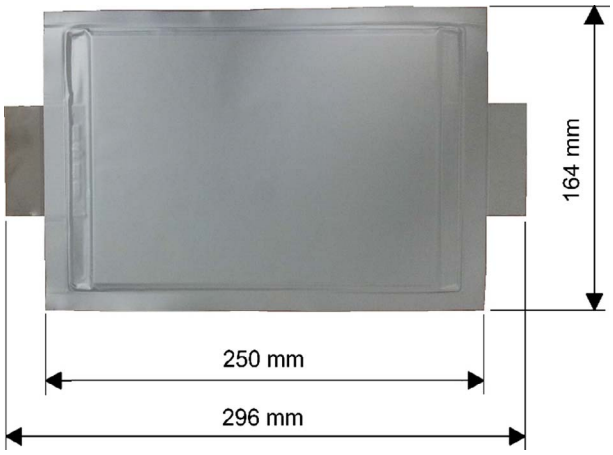

Fig. 1. Lithops pouch-type cell.

For electrochemical systems with good transport properties, the heat from mixing can usually be neglected [15]. In addition, if all species taking part in the electrochemical reactions within the cell are in the same phase, the phase change terms are zero. Therefore, a simplified form of the equation proposed by Bernardi [14] can be used as the expression for the heat source in the lithium-ion cell tested in this paper:

$$\dot{q}_T = I\cdot(V - U^{avg}) + I\cdot T\cdot\frac{\partial U^{avg}}{\partial T} \tag{1}$$

where:

I is the current delivered by the Li-ion cell, the difference between V and U^{avg} is the cell overpotential, and it is indicative of the irreversibility such as ohmic losses in the cell, charge transfer overpotentials at the interface, and mass transfer limitations.

The first term on the right side of the Eq. (1), the overpotential multiplied by the current, is known as the polarization heat and is composed of the Joule heating within the battery as well as the energy dissipated in electrode overpotential. This term is always positive (the sign convention adopted here makes the current positive during charge).

This equation takes the form of the heat source that is most commonly encountered in literature [16–19].

The overpotential heat can be described using the equation:

$$\dot{q}_P = I\cdot(V - U^{avg}) = I^2\cdot R_{int} \tag{2}$$

In this way, the overpotential heat can be determined from the internal resistance, R_{int}. This yields the equation for the heat source:

$$\dot{q}_T = I^2\cdot R_{int} + I\cdot T\cdot\frac{\partial U^{avg}}{\partial T} \tag{3}$$

The second term on the right side of the Eq. (3) is the reversible entropic heat, which is related to the entropy change, and the potential derivative with respect to temperature is often referred to as the entropic heat coefficient or temperature coefficient. This term can be either positive or negative. In order to avoid confusion, from now on the term $\partial U^{avg}/\partial T$ will be represented by dV/dT.

Positive (negative) values indicate that the effect of entropic heat is exothermic (endothermic) during discharging/charging processes.