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Research Paper

Coupled electrochemical and thermal battery models for thermal management of prismatic automotive cells

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HIGHLIGHTS

- Novel 3D electrochemical model with heat generation, gives thermal field in prismatic cells.
- Advance is coupled electrochemical-thermal field, in past, thermal generation separate.
- Thermal profiles determined in new 30 A h cells for US06 drive cycles, with cooling.
- Liquid cooling gives temperature increase of 2C, 9C for forced air, 15C for passive air.

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ABSTRACT

This study combines a two-dimensional Ohm's law finite-volume approach determining the current distribution in prismatic battery cells with a simplified electrochemical model for the thermal state of automotive battery packs. The objective was to develop a simulation tool for assessing the effect of cooling effort applied to automotive battery packs under real-life usage conditions. The Ohm's law model was enhanced by imparting a chemical and physical basis to source terms previously found empirically. This simulation was applied to 2D electrode sheets, determining thermal generation values that were mapped volumetrically into a thermal simulation, which in turn, updated the electrochemical simulation. Battery parameters, along with capacity fade kinetics were determined by fitting experimental data to simulated results. Dynamometer data from tests under reference drive cycles provided current demands on battery cells. Thermal profiles simulated for 30 A h prismatic cells at different cooling levels. Passive and forced air cooling simulations both gave endpoint temperatures upwards of 40 °C (313 K), considered excessive for preserving the battery life. A simulation scenario which reflected a liquid cooling system kept the temperature gain for a US06 drive cycle to about 2 K. With liquid cooling, an automotive battery is better protected against thermally driven degradation.

1. Introduction

At present there are significant efforts being made in many areas with electric vehicles aimed to establish their viability in the automotive marketplace. Well known energy, economic and environmental drivers are giving impetus to these efforts [1,2]. Engineering efforts are focussed on steadily improving vehicle performance in the areas of power delivery, safe operation and increasing autonomous driving range to win consumer confidence. Such objectives place ever increasing performance demands on the battery packs in electric vehicles. One particular consequence of the technical trajectory described above, is a growing appreciation of the need to employ effective thermal management to automotive battery packs. Concretely, as relates to this present study, the use of battery materials with ever increasing energy densities [3], coupled with severe performance demands required by driving, serve to generate significant heat inside automotive battery packs. This circumstance is further exacerbated in automotive applications by the limited amount of under the hood space and volume available in which to configure battery packs. It is well known that battery operation at elevated temperatures contributes to more extensive cell degradation and will shorten the service life of a battery pack. A number of mitigation strategies are currently employed for thermal management such as oversized pack design, highly conservative battery management systems as well the implementation of active battery cooling systems [4,5]. In view of all the factors which create this situation, the present study aims to explore the impact of the

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thermal management system in automotive battery packs and to develop a framework that could be used to predict the long term service life of a battery pack as a function of its thermal management system.

In the literature, there are numerous examples of coupled electrochemical-thermal models that employ different combinations of electrochemical (SPM, P2D, P3D, equivalent circuit) and thermal (1D, 2D, 3D) treatments. Some standard references which nicely introduce the subject can be cited [6–8]. These kinds of studies are too numerous to explore and cite exhaustively, so the focus here for investigating the literature was aimed at coupled electrochemical and thermal models which have been adapted and applied for simulating automotive battery operation integrated with cooling systems. Among recent such studies, a paper by Fang et al. [7] provided an initial effort in this area, beginning with a 1D battery model, and simulating extremely high heat transfer coefficient levels over a large 30×30 cm cell surface, according to experimental conditions for a test cell. Another study [9] presented an electrochemical-thermal formulation in pseudo-2D which was mainly focussed on orthogonal collocation transforms, with heat transfer in automotive batteries as a test platform for the mathematical approach. As such, unrealistic heat transfer conditions along with low heat transfer coefficients over only one thermal axis were considered. As well, a number of studies have placed the primary focus on the cooling operations, while attempting to impart some realistic environment and thermal loads associated with automobile operation. In one case, a prismatic cell bank was studied with bulk flow forced air cooling [10]. Here, battery function was treated as a heat source, only a simple thermal model was employed with the emphasis of the study on the inter-cell spacing configurations. Simulation work aimed at electric vehicle drive cycles has been undertaken [11], but drive cycles themselves were not actually simulated, rather a number of test situations with various current levels and pulsing conditions. The electrochemical model was derived from the Gu model [12], and featured thermal model coupled with their electrochemical model applied to a prismatic configuration under air cooling conditions. Similarly, also using a Gu-type formulation, a decoupled three-dimensional battery pack thermal model [13] was developed to estimate the temperature variation of battery cells across a pack along with temperature fields in individual battery cells in the pack. A comprehensive study of cooling systems was modeled [14] by Hamut et al., which featured a full thermal model of prismatic cells with simply assuming a range of heat generation rates from an operating battery. The study recommended liquid cooling systems for controlling temperature increases and minimizing thermal gradients within cells.

Some previous studies have conducted some preliminary research on the subject of adapting and applying simulated battery operation integrated with cooling systems in a dynamic manner as would be reflected by real-world driving. There have been studies which have considered the design and configuration of forced air cooling systems for automotive battery packs [15,16]. In these cases, the research was focussed on the heat transfer part of the system, concentrating on the effects of geometric configurations, and air flow routes, with the battery function present in the model only as a heat source. The extent of the battery heat generation was based on experimental measurements with prismatic automotive cells. Some attention has also been given to liquid cooling in battery packs. These have generally been engineering type studies, focussing on the design and general performance of the cooling system using measured thermal outputs from cells or packs determined from simple tests normally done at constant current [17,18]. A more sophisticated treatment of the battery function was provided in a liquid cooling system study by Yeow et al. [19], where the thermal generation from the battery was modeled as an empirical function of state of charge and operating temperature. The focus in these cases was on the operation of the cooling system. A more comprehensive modeling effort [20] compared 35 and 70 A h cells to assess the performance limits of a cooling system, noting that enlarged and enhanced cooling system would be required for the higher capacity cells discharging at a rate of 4C to keep the temperature rise less than 10 °C. Only one very recent paper was found in the literature where a coupled electrochemical and thermal model was employed, using commercial software, with some preliminary results presented for pulsing current loading at 170 A [21].

Finally, for the present project, a later objective is the full coupling of the models developed here with a dynamic cooling system which would include serpentine coolant channel layouts in cooling plates. Such a coupled interaction would require an electrochemical-thermal battery model running alongside a spatial resolved CFD based heat transfer model, hence the present focus on thermal effects in prismatic cells, and the body of literature expressly aimed at this subject. Further, a note on the extending the scope of applicability of this approach can be made. As long as the battery electrode layers function in a prismatic cell configuration [22], the present approach could be adapted to batteries with different basis electrochemical bases such as lithium-air batteries, which have fundamentally distinct electrochemical behaviour as outlined in some recent papers [23,24]. By similar reasoning, catastrophic episodes such as short-circuiting leading to thermal runaway have been modeled [25], and the present approach could overlay this intense and rapid heat-generation scenario to assess how various levels of thermal management would cope with it. The general and fundamental nature of these simulation models make them readily adaptable for the studies of present concern such as comparing different battery chemistries or usage scenarios with electric vehicles in cold weather environments.

2. Model development

The numerical models developed here are rooted in the discretized Ohm's Law approach developed by Kim et al. [26–29]. The Kim models are implemented on prismatic cell geometries and provide a means for determining a non-uniform current distribution over the surface of the current collectors. As originally developed, the concept of the Kim model consisted of applying Ohm's Law over a conducting medium, with source terms representing current flowing into or out of an external electrode layer. For example, in discharge mode, the anode side equation would have source terms representing current loss (i.e.; have a negative value), while the cathode side equation would have source terms accounting for incoming current. The source terms in the Kim model were determined empirically. An objective of the present paper is to enhance the Kim model to replace the empirical source terms with terms based on the chemistry and physics of the charge and discharge processes which occur in the electrode layers of a battery cell. To achieve this, battery function, as described by the single-particle model (SPM) [30] was integrated into the Kim model implemented on prismatic cells. A further step was then to integrate the Kim-SPM with a thermal energy balance to simultaneously model the thermal state and behaviour of an operating prismatic cell.

2.1. Kim model

The Kim model is applied to two parallel-plate electrodes of a prismatic type battery cell. Current enters (in discharge mode) via the tab on the anode side current collector, is distributed over the anode side current collector plate from which it enters an adjoining electrode layer in a perpendicular direction. Similarly, the local currents which enter the electrode layer from the anode side, also pass through the cathode side electrode layer prior to entering the cathode side current collector. The current then flows through the cathode side current collector and exits via the cathode side tab. Fig. 1A is a schematic depiction of the simulation domain configuration.

A 30 A h prismatic cell used in a present-day electric vehicle with a LiNMC cathode and a graphite anode was simulated. The cells consisted of a stack of 24 electrode sheets inside a polymeric casing. The sheets had a height of 17.7 mm and a width of 12.7 mm. The stack of electrode sheets was 5 mm thick, and they were encased in a polymeric pouch of