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A novel thermal swelling model for a rechargeable lithium-ion battery cell

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HIGHLIGHTS

- Thermal expansion exhibits nonlinear characteristics with respect to temperature.
- Thermal expansion depends on the SOC and the location on the battery.
- We develop a thermal swelling model with calibrated coefficients from experiments.
- The model uses a 1-D heat transfer approximation to predict the core temperature.
- The model accurately predicts thermal swelling during operation and relaxation.

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ABSTRACT

The thermal swelling of rechargeable lithium-ion battery cells is investigated as a function of the charge state and the charge/discharge rate. The thermal swelling shows significant dependency on the state of charge and the charge rate. The thermal swelling follows a quadratic form at low temperatures, and shows linear characteristics with respect to temperature at high temperatures in free-swelling conditions. Moreover, the equivalent coefficient of thermal expansion is much larger than that of each electrode and host materials, suggesting that the separator and the complex shape of the cell play a critical role in thermal expansion. Based on the experimental characterization, a novel thermal swelling model is proposed. The model introduces an equivalent coefficient of thermal expansion for the cell and also considers the temperature distribution throughout the battery by using heat transfer theory. The comparison between the proposed model and experiments demonstrates that the model accurately predicts thermal swelling at a variety of charge/discharge rates during operation and relaxation periods. The model is relatively simple yet very accurate. Hence, it can be useful for battery management applied to prolong the cycle life of cells and packs.

1. Introduction

Concerns for energy security, instability in world oil markets, and limitations of carbon emissions have accelerated the development of eco-friendly, high-efficiency automobiles. This drives automobile industries toward the development of vehicle electrification technology. Electrified vehicles currently use lithium-ion (Li-ion) batteries as the reversible power source. Li-ion batteries have advantages such as high power/energy density, high potential, and low self-discharge rate. They are also environmentally friendly and have a long life cycle [1–3].

While vehicle electrification with the advent of the Li-ion batteries [4] enhances fuel efficiency and reduces CO_2 emissions, many challenges still exist when using Li-ion batteries such as their limited performance at low temperatures [5] and their thermal runaway [6]. Especially, extensive research on vehicle electrification has been driven by stringent safety standards for air and ground applications. Therefore, recent research focuses on the thermal distribution and the heat dissipation of Li-ion battery packs [7,8] as elevated temperatures not only can cause thermal runaway but can also degrade battery life. A variety of heat transfer models have been created for the Li-ion batteries and validated through experiments [9–12]. Many methods and strategies for use in battery management systems (BMS) have been developed to mitigate the safety concerns while enhancing efficiency and capabilities [13,14,24].

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Heat is generated in a Li-ion battery cell from two sources: entropy change and Joule heat. Entropy compensates the residual energy in the energy conversion process between the enthalpy and the Gibbs free energy [15]. Entropy heat is therefore reversible; it is generally endothermic during charge and exothermic during discharge. Joule heat is due to the internal resistance of the cell components such as the positive/negative electrodes and the separator. Joule heat is irreversible and exothermic regardless of the charge process. These sources of heat not only change the temperature but also change the volume of the Li-ion battery. This volume change causes additional periodic thermal stress during operation and affects the lifespan of the cells and packs. Therefore, many efforts have been devoted to characterize the thermal expansion of the host materials in micro-scale [16–18]. These studies provide a useful foundation for understanding the thermal characteristics of the active materials. However, the dynamic thermal mechanics at the cell-level are more complicated because of the hundreds of contact surfaces between electrodes and mechanical constraints such as wounding shape of the jellyroll and clamping current collectors with bus bars in the edge sides. Our previous study showed for the first time that thermal swelling is similar in order of magnitude with Li-ion intercalation swelling and thereby far from insignificant [19]. However, studies of thermal expansion on the cell-level are still few, making it difficult to estimate the thermal stress due to thermal expansion, while the swelling due to electrochemical reaction, i.e. Li-ion intercalation, has intensively been investigated from micro-scale to macro-scale [20–23]. Especially, the most important property which comes from both the material and its structure inside the cell, i.e. the equivalent coefficient of thermal expansion on the cell-level, was never reported before, even though this property is crucial not only to predict the dynamic thermal mechanics of battery cells but also to estimate periodic thermal stress/strain on packs. Moreover, the modeling of the thermal expansion on the cell-level with the measured material property has not been investigated in great detail, although characterizing the thermal expansion has become important to prolong the life of Li-ion batteries. The limited information about thermal stress and strain on the cell-level stimulates the quantification of thermal stress and strain on the battery cells and packs, which affect the battery performance in packs.

In this paper, we report results and models obtained by measuring the expansion of a cell. High-precision displacement sensors were used to measure the cell-level swelling arising from charge/discharge of an unconstrained graphite/nickel-manganese-cobalt-oxide (NMC) cell whose temperature was regulated in a thermal chamber. The measured thermal expansion was observed to vary significantly with experimental control parameters and also was observed to exhibit nonlinear characteristics with respect to temperature. An equivalent coefficient of the thermal expansion was calculated as a function of the state-of-charge (SOC) at a variety of locations. A novel thermal swelling model is proposed based on the experimental results. The proposed model uses the measured equivalent coefficient of thermal expansion to estimate the thermal swelling. Moreover, a 1-D heat conduction model is introduced to account for the temperature distribution through the cell for a more accurate estimation of thermal swelling. The proposed model was verified by comparisons with experimental data consisting of thermal expansion at various C-rates, both during operation and relaxation periods. The experimental validations confirm that the proposed model accurately predicts experimental observations in a variety of operational conditions. Such an accurately model, able to estimate cell thermal behavior, may be beneficial to the design and management of not only single cells but also battery packs.

2. Experiments

This study used a flat-wound type prismatic 5Ah Li-ion cell obtained from a Ford Fusion HEV battery pack. Detailed information of the Li-ion cell is available in Ref. [19].

The free swelling of the cell was measured with high-precision contact-type displacement sensors with 1 μm accuracy and 0.1 μm resolution (Keyence GT2-H12KL, Japan). The sensor head creates a contact force on the battery surface of less than 0.3 N. The sensor was installed in a fixture as shown in Fig. 1. The fixture was made from ABS plastic using a rapid-prototyping machine (Dimension Elite FDM, USA). The prismatic cell was constrained at its eight corners with ABS plastic set-screws in the fixture, but was otherwise unconstrained. The fixture was placed inside a thermal chamber (ESPEC BTZ-133, Japan) with controlled desired temperature. Two thermocouples were also used. One thermocouple was installed on the center of the cell to measure cell surface temperature (in a location that avoided interference with the displacement sensors). The other thermocouple was installed between the fixture and the cell to measure near-surface ambient temperature.

A first experiment was carried out to assess the thermal expansion characteristics of the cell over the SOC. In this experiment, relative thermal expansion in the z direction, which is perpendicular to the multi-layer electrode sandwich, was measured with a variety of SOCs at five locations labeled 1–5 in Fig. 1. Prior to discharge, the battery was fully charged using a standard constant current, constant voltage charging profile at 2A (0.4C) at 25 °C; the voltage was clamped after reaching 4.1 V, at which it was held until the current tapered to C/100 (50 mA). To obtain the desired SOC, the battery was discharged with a 0.4C current for an appropriate time. For example, 1.25 h discharge time was used to obtain a 50% SOC. The battery was allowed to rest at open circuit for 1 h to ensure full relaxation at the end of discharge. Then, the temperature of the thermal chamber was incrementally changed from 5 °C to 45 °C with 5 °C increments. Each temperature variation was followed by 5 h of rest time to ensure thermal equilibrium. This procedure was repeated from 0% to 100% SOC with 25% SOC increments.

The second experiment repeated the same temperature profile (from 5 °C to 45 °C with a 5 °C increment) of the first experiment with an aluminum block instead of the cell. That was done to characterize the thermal expansion of the fixture and the sensors because they also expand or shrink when the ambient temperature varies. Five sensors were installed on one side of the cell at the same locations as in the first experiment. One other sensor was installed in the center of the opposite face of the cell (without contacting the cell) to observe the thermal behavior of the sensor itself.

In a third experiment, swelling at several C-rates was measured for the validation of the thermal swelling model. The net displacement at the center of the battery was measured with respect to the charge state during discharge using a standard constant current discharging profile. All discharges were performed down to 3.0 V. Measurements with exterior thermocouples showed that the lowest current used, 0.2C (1A), did not cause significant heating. The battery-cell surface remained within 0.1 °C of the 25 °C ambient temperature during discharge. Data at 0.2C therefore allows direct correlations to be made between swelling and Li-ion intercalation in a cell sandwich without significant convolution by thermal expansion. In contrast, the cell surface temperature deviated more significantly from the ambient at high C-rate tests where temperature variations produced considerable thermal swelling.

In a fourth and last experiment, pulse excitation experiment was carried out to assess the viability of the proposed model in HEVs.