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In-plane nonuniform temperature effects on the performance of a large-format lithium-ion pouch cell

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HIGHLIGHTS

- Controlled in-plane temperature distributions to emulate an edge-heat transfer process.
- Hybrid Pulse Power Characterization and US06 dynamic charge depleting power profiles.
- Increased temperature nonuniformity reduces resistance for the HPPC results.
- Increased temperature nonuniformity increases resistance for the US06 results.

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ABSTRACT

Due to the temperature sensitive behavior of lithium-ion batteries a thermal management system (TMS) is typically integrated into the battery pack design. This system plays a crucial role in the total battery pack performance. During operation the TMS will induce nonuniform temperature distributions within the cells of the pack, due to relatively low cell thermal conductivity. However, limited research has been published regarding the effects of thermal nonuniformity throughout a cell, module, or pack. Understanding these effects will be beneficial to heat exchanger design and TMS control strategy optimization. Here, an experimental investigation is performed where fixed one-dimensional temperature distributions, emulating the effects of edge-based heat transfer, are applied across the face of a 10Ah NiCoMn Li-ion pouch cell. Average cell temperature conditions of 15, 25, and 35 °C with edge-to-edge temperature differences (ΔT) of 0, 5, 10, and 20 °C are applied. At each thermal treatment the effects on: (1) the pulse resistance at 50% state of charge, (2) the bulk resistance on a Charge-Depleting US06 power profile, and (3) the overpotential during Constant-Current charge are investigated. Pulse resistance is decreased with increased ΔT. However, the discharge resistance on the Charge-Depleting cycle was increased with increased ΔT. The Constant-Current charging overpotential (and therefore resistance) was also increased with increased ΔT. All effects are largest at 15 °C, and negligible at 35 °C.

1. Introduction

Commercially available Li-ion cells presently have high temperature sensitivity with regards to performance and lifetime. For example, cell lifetimes can be severely reduced by increases in average lifetime temperature from standard conditions [1], while short-term performance is improved greatly at higher average cell temperatures. As a result, one must carefully balance the temperature control of a battery pack to simultaneously optimize the performance and lifetime of the battery. Empirical studies [2–7] and model development [8–15] investigating the effect that uniform average temperature has on cell performance and life has been understood for some time. Therefore, advanced thermal management systems (TMS) capable of maintaining the battery temperature regardless of ambient conditions are a critical component included in lithium-ion battery packs [16,17].

For larger battery pack applications (>15 kW h) the use of modules containing several stacked Li-ion pouch cells on the order of 15Ah has become common [18]. Both the internal nonuniform cell heating and external heat transfer from the TMS will cause internal cell temperature distributions, which may grow in excess of 10 °C [17–19]. Internal temperature distributions are known to cause internal state of charge (SOC) imbalances [20,21], where regions of a single cell become more severely depleted than others. Models ranging vastly in complexity [20–28] have been developed to study spatial distributions of current (and thus local internal SOC), as

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well as temperature within large format cells. However, none of these models have been explicitly used to study the preformance effect caused by the degree of temperature inhomogeneity.

Several TMS heat exchanger (HX) and HX-to-cell interface techniques exist and a few pouch cell configurations are illustrated in Fig. 1. For example, stamped aluminum coolant plates (<1 mm thick) interleaved between cells is shown in Fig. 1c. The coolant plates are in contact with the broad face of the pouch cell and coolant is pumped through the plates to improve heat transfer. This is considered a face-cooling technique and heat is transferred in the through-plane cell direction. To contrast this an edge-cooling strategy is illustrated in Fig. 1d where a coolant plate is attached to the edge of a pouch cell, transferring heat in the in-plane cell direction. The edge-cooling techniques are generally less complex than face-cooling methods, from a system design perspective.[1]

When comparing different TMS designs the optimization process attempts to minimize the heat exchanger mass, volume, and cost, while taking into account the effect each design has on the power and lifetime capability of the battery. An important constraint presently used in TMS design is the degree of temperature nonuniformity within the battery pack. Designing for less than 5 °C maximum temperature distribution is common practice. However, a rather small amount of research has been published on developing an understanding of how thermal nonuniformity effects the power [29,30] and lifetime [31] of a Li-ion cell. As this constraint has a significant impact on TMS design selection it is important to quantify. The argument being made here is that understanding the effect of thermal nonuniformity on batteries will enable greater optimization of thermal management system designs and control strategies. Additionally, advanced spatially resolved thermally-coupled models lack sufficient experimental validation of spatially nonuniform temperature effects, and therefore this experimental investigation will also be beneficial from a model validation perspective.

This work experimentally investigates the effect of temperature nonuniformity on a Li-ion pouch cell of 10Ah nominal capacity. Controlled nonuniform thermal conditions are placed on the cell for Hybrid Pulse Power Characterization (HPPC) tests in order to characterize the short time scale behavior as a function of thermal nonuniformity. Second, the cell is tested using a dynamic power profile derived from a US06 driving schedule [32]. The thermal conditions were such that the average temperature ($\overline{T}$), of the cell and the edge-to-edge temperature difference (ΔT), were held constant during all tests. Three average cell temperatures of 15, 25, and 35 °C were used for both the HPPC and US06 testing. For the HPPC testing at each $\overline{T}$ the cell was placed under three different ΔT conditions of 0, 10, and 20 °C. The US06 ΔT conditions were 0, 5, 10, and 20 °C.

The HPPC results developed here follow similarly with the work of Troxler et al. [29], in that with increased ΔT the effective cell resistance was reduced, causing a performance improvement. Troxler placed a linear temperature profile through-plane (x-coordinate of Fig. 1) on a pouch cell, which may be expressed by Eq. (1.1).

$$T(x) = \frac{\Delta T}{L}x + \left(\overline{T} - \frac{1}{2}\Delta T\right) \tag{1.1}$$

Here L is the length of the cell dimension in the direction the temperature gradient is placed. In Troxler's work that is the pouch cell thickenss. In a pouch cell the through-plane direction consists of several cell sandwiches connected in parallel via the current collector tabs. Therefore, they proposed a model for explaining the nonuniform temperature effect on resistance by computing the equivalent resistance that results from connecting a set of resistors in parallel, where each resistor is a function of the respective local temperature, as in Eq. (1.2).

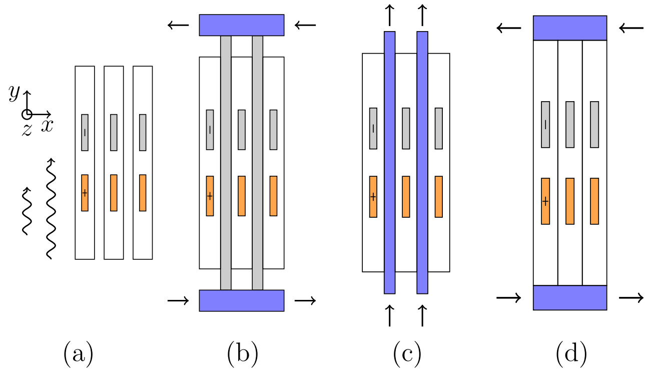

Fig. 1. Pouch cell thermal management. Top view of stacked pouch cells, with tabs sticking out of the page in the z-coordinate. (a) Direct fluid heat exchange. (b) Indirect fluid heat exchange. Edge-Fin style. (c) Indirect fluid heat exchange. Face style. (d) Indirect fluid heat exchange. Edge style.

$$R_{eff} = \left[\sum_{i=0}^{N} 1/R(T(x_i))\right]^{-1} \tag{1.2}$$

where, R is some resistance parameter that is a function of temperature, and R_{eff} is the effective resistance under the nonuniform temperature profile. The spatial index is i, and the total number of points used along the spatial coordinate is denoted by N. In Troxler's case N refers to the number of individual cell sandwiches that are stacked and connected electrically in parallel inside the single pouch cell. Their model is referred to in this paper as the Through-Plane-Model (TPM). Troxler fit an Arrhenius Eq. (1.3) to the Electrochemical Impedance Spectroscopy (EIS) derived solid-electrolyte-interphase (SEI) resistance and the charge-transfer resistance vs. temperature data.

$$R(T) = R_{ref} \exp\left[\frac{-E_a}{R_{gas}}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{1.3}$$

The resistance at the reference temperature is denoted by R_{ref}, R_{gas} is the ideal gas constant, T_{ref} is the reference temperature which is the temperature at which the reference resistance refers to (typically 25 °C), and T is the cell temperature. The activation energy, E_a, controls the temperature sensitivity of the resistance. Given an Arrhenius temperature sensitivity and a linear temperature profile, the equivalent resistance must be of lower magnitude than the resistance at the average cell temperature. The magnitude of the ΔT effect is related to the activation energy in the Arrhenius equation, and therefore cells with larger E_a (i.e., higher temperature sensitivity) will be more sensitive to temperature nonuniformity. The TPM is able to explain both the observed ΔT effect as well as the increased impact that a given ΔT has at lower average cell temperatures, which is due to the exponentially increasing temperature sensitivity at lower average cell temperatures. However, our results presented here show that the Charge-Depleting data conflicts with the TPM proposed by Troxler. The effective bulk discharge resistance computed using the US06 data shows an increase with increased ΔT, or a performance reduction. The Constant Current (CC) portion of the recharge after each Charge-Depleting test also shows a performance reduction. For all tests the effect of ΔT is

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[1] The through-plane volume-averaged thermal conductivity of a Li-ion pouch cell is on the order of 1 W/(m-K), whereas the in-plane volume-averaged thermal conductivity is on the order of 20 W/(m-K). However, due to the advantageous geometry (L/A_{crz}) of the face-cooling technique the effective thermal resistance of an edge-cooling technique is still approximately five times larger, for traditionally shaped pouch cells.