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Examining temporal and spatial variations of internal temperature in large-format laminated battery with embedded thermocouples

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HIGHLIGHTS

- Thermocouples embedded inside a cell detected significant temperature variation.
- Internal temperature differed appreciably from the surface for thin laminated cell.
- Center layer thermal response time was 485–620 s, 27–70 s larger than the surface.
- In-plane temperature variation was much larger than through-plane direction.
- Forced convection was effective in suppressing temperature rise and variation.

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ABSTRACT

Information on battery internal temperature is valuable to enhance the understanding of thermo-electrochemical reactions, to validate simulation models, and to refine battery thermal design. In this study, 12 thermocouples are embedded at strategically-chosen locations inside a 25 Ah laminated lithium-ion battery. Another 12 thermocouples are attached at the corresponding locations on the surface. The temporal and spatial variations of the temperature are measured at a series of discharge rates under different thermal conditions. The thermal response of these locations is also analyzed. The major findings include: First, the internal temperatures could differ from the surface for as large as 1.1 °C, even for a thin laminated cell. Second, the time constants of thermal response at the internal locations are generally dozens of seconds larger than on the surface. Third, the internal variation in the plane direction reaches above 10 °C under adiabatic 1.5 C discharge, much larger than in the through-plane direction, indicating the in-plane heat conductivity needs improvement. Finally, forced convection is effective to suppress the temperature rise as well as the variation. The direct measurement of internal temperature initiated in this study paves the way for implanting sensors/microchips in single cell to extract multiple physico-electrochemical signals simultaneously.

1. Introduction

Battery temperature is measured for experimental research or monitored for the management of BTMS (battery thermal management system) of electric vehicles. The measurement methods of battery temperature could be classified into three types according to the location of temperature sensors.

(1) First, temperature sensors are located outside individual cell. Generally, for battery packs of commercialized electric vehicles, most of the existing methods use the one-point temperature on the cell surface to represent the overall state of the cell (2010 Toyota Prius) [1–4]. Besides cell temperature monitoring, with other sensors located in the cooling system (GM Volt) or on top of the sub-modules (Tesla Roadster), the multi-point temperature distribution of the battery pack is obtained.
(2) Second, single temperature sensor has been reported mounted on top of the cell and sealed inside [5], but neither of them is located between the electrodes. Therefore, it's difficult to determine whether the internal temperature is monitored. Meanwhile, with the single location of temperature sensor, it's impossible to measure the temperature distribution inside the cell.

The above two types of measurement methods adopt the temperature at single location out of the electrodes to evaluate cell

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thermal conditions. For small cells used in electronic products like cell phones and laptops, the associated error may be negligible. However, for large-format traction battery, the temperature variation at different locations inside the battery develops, and the temperature at one point on the surface can no longer represent the overall state. Under severe nonuniform temperature distribution, local hot spots may form, impairing cell durability or even triggering safety problems.

(3) Third, the sensors are inserted deeply into the cell to obtain internal temperature.

The information of battery internal temperature is valuable to reveal the location of internal hot spots/zones, to elucidate the mechanism of heat accumulation, and to refine the thermal design of the cells in aspects like the structure (cylindrical, prismatic or laminated), the cell capacity, and the configuration of the key components like the tabs. Besides helping to improve cell design, the information of internal temperature is also needed to achieve a sufficient validation of existing thermo-electrochemical simulation models. The existing battery models are already rather sophisticated and are capable of describing the voltage/current/temperature/Li^+ ion concentration in each individual electrode layer [6–8]. However, only the surface temperature, usually at one location is used to validate these models. The scarcity of internal information hinders the integrality of the model validation, leaving its accuracy and predicting capability questionable.

Notwithstanding the importance of the internal temperature, the trials to obtain the information are rarely found in the literature, probably due to the difficulty involved in introducing sensors into a single cell.

Christophe Forgez [9] designed a plug-in measurement method to detect the internal temperature of a cylindrical 26650 lithium iron phosphate battery. A T type thermocouple was inserted into the hole drilled on the top of the cylinder to measure the internal temperature of the battery. Several measures were taken to enhance the safety of the operation. First, the whole process was carried out in the argon glove box to ensure an inert environment; Second, the battery was nearly fully discharged before the drilling. Moreover, the hole was sealed with resin after the thermocouple was inserted.

Chi-Yuan Lee [10] fabricated a flexible micro temperature sensor by depositing the erosion-resistant parylene and other sensor material layer-by-layer using physical vapor deposition (PVD) technique. Two of these sensors were inserted into a spirally-wound prismatic lithium-ion battery to measure the internal temperature. Then, micro electro-mechanical systems (MEMS) were utilized to develop integrated micro temperature and voltage sensors on the same piece of stainless steel foil, and six micro sensors were embedded in the flow field of a high-temperature fuel cell stack to monitor local temperature and voltage in situ [11].

In this study, instead of being inserted into the battery afterward, multiple thermocouples were embedded between the layers of electrodes of a laminated cell during the manufacturing process. It had the following advantages: First, the sensors with reliable insulation were embedded during the manufacturing process to avoid piercing the internal structure and triggering internal short; Second, the vacuum degree and the atmosphere inside the battery were kept essentially unchanged from an ordinary cell, therefore the battery was more reliable and might achieve longer cycle life before the failure; Third, multiple sensors could be readily accommodated and the location of each sensor could be precisely controlled, which was critical to quantitatively distinguish the temperature of different locations. Using the thermocouple-embedded cell, the temporal and spatial variations of the temperature were measured during constant-current discharge at a series of C-rates and different thermal boundary conditions.

Table 1
The specification of the two cells.

Cell specification	Value	
	Cell 1	Cell 2
Capacity (1/3 C)	5 Ah	25 Ah
Nominal voltage	3.8 V	
Nominal resistance (1 kHz)	5 mΩ	1 mΩ
EODV (end of discharge voltage)	3 V	
Recommended charging method	CC–CV	
EOCV (end of charge voltage)	4.2 V	

To the author's knowledge, this study initiated the direct measurement of the internal temperature at multiple locations inside large-format laminated traction battery. The measured temperature variation under different thermal boundary conditions revealed the thermal property of the tested cell, identified the direction for the improvement of cell thermal design and the ways for effective thermal management. The measured results are currently being used to validate our thermo-electrochemical model. Moreover, it has explored the feasibility of implanting sensors into a single cell, which was previously considered fragile and zero-tolerant of intruders. This attempt paves the way for the research of smart cell, a cell that can monitor and manage itself, with sensors sandwiched between the electrode layers and microchips sealed inside.

2. Specifications of the tested cells and locations of the embedded thermocouples

The constant-current discharge experiments under a series of C-rate in different thermal boundary conditions were carried out on two types of sensor-embedded $LiMn_2O_4$/graphite laminated cells, 5 Ah and 25 Ah. The specifications of the two cells are shown in Table 1.

Fig. 1 shows the EIS (electrochemical impedance spectroscopy) results of the sensor-embedded 25 Ah cell and another ordinary (without embedded sensor) 25 Ah cell. It was concluded that the EIS result of the sensor-embedded 25 Ah cell was quite similar with ordinary cell. The cell consistency was proved to be satisfactory, and the thermal behavior of the sensor-embedded 25 Ah cell should be representative of this cell model.

The specifications of the sensors embedded inside the cells are shown in Table 2.

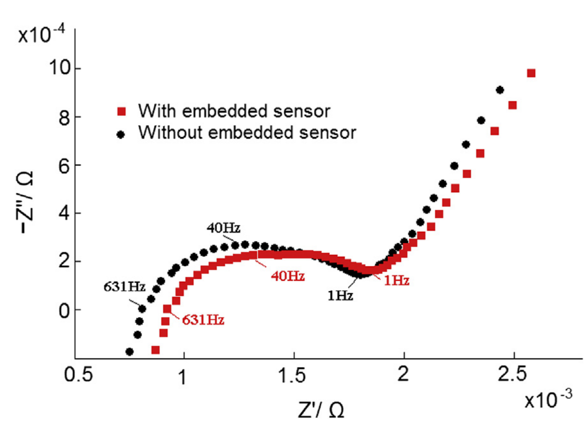

Fig. 1. The EIS results of the two 25 Ah cells with and without embedded sensors.