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Non-invasive measurement of internal temperature of a cylindrical Li-ion cell during high-rate discharge

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ABSTRACT

Li-ion cells are a technologically important class of devices for electrochemical energy storage and conversion. Overheating of a Li-ion cell during operation is undesirable as it directly affects performance and safety. Although a number of methods have been used for temperature measurement in Li-ion cells, there is a lack of non-invasive techniques to determine the peak temperature at the core of the cell. Measuring only the outside surface temperature, while straightforward, is not sufficient since the core temperature may be much higher. This paper presents non-invasive measurement of the core temperature of a Li-ion cell using a recently developed technique that utilizes space and time integrals of the measured temperature field at the outside surface. The surface temperature field of an operating Li-ion cell is measured using infrared thermography at multiple discharge rates up to 10C, using which, the core temperature is predicted as a function of time. In each case, there is excellent agreement throughout the discharge period between the predicted core temperature and measurements from a thermocouple embedded at the core of the cell. These measurements quantify the temperature gradient within the cell, which is particularly high at large discharge rates. The non-invasive core measurement methods described here may contribute towards performance optimization and improved safety of Li-ion cells.

1. Introduction

Accurate measurement of temperature in a Li-ion cell is a critical research challenge for ensuring performance, safety and reliability of systems that utilize Li-ion cells for energy conversion and storage [1–3]. Temperature rise occurs in a Li-ion cell due to heat generation during energy conversion, particularly at high discharge rates [4–6]. The amount of heat generated in a typical cylindrical 26650 Li-ion cell is not extremely large. For example, about 10W heat generation has been reported during discharge at an aggressive 10C rate [7,8]. For reference, the C-rate of a charge/discharge process is defined as the reciprocal of the number of hours needed to completely charge or discharge the cell [1,7]. However, due to poor thermal conductance of the cell [9] resulting from material and interfacial thermal resistances in the cell [10], this causes significant temperature rise [11,12], particularly in the core of the cell, where heat accumulation tends to occur due to the lack of a direct access for heat removal [13]. While high core temperature may result in some performance improvement due to reduced internal resistance, it is also known that high cell temperature increases the rate of capacity fade [14,15]. Further, in many cases, the Battery Management System (BMS) may throttle cell power in response to a high cell temperature to keep the cell within a safe envelope, thereby resulting in reduced performance. This necessitates the design and implementation of an effective thermal management strategy in order to keep the cell temperature below a threshold value and prevent undesirable conditions such as thermal runaway [16–18]. A number of thermal management strategies have been reported in the past, which have been well covered by recent review articles [14,15,19]. Most thermal management techniques focus on heat removal from the outside surface of the cell. This is accomplished either by the flow of an appropriate coolant such as air or water over the cell surface, or by cold plates [20], heat pipes [21] or phase change materials [22] in the battery pack. Other more intrusive thermal management techniques include the use of electrolyte as a coolant [23], heat absorption from current collector foils [24], as well as the integration of a heat pipe protruding out of the cell [13].

Accurate measurement of temperature of the cell, particularly the peak temperature that occurs at the core of the cell is critical for effective thermal management and thermal control. Measurement of surface temperature alone does not provide much information about the core temperature since the surface temperature

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may not rise much even when the core is much hotter and is in urgent need for cooling. In past experiments, for example, a temperature difference of as much as 15 °C has been reported between surface and core temperatures of a Li-ion cell undergoing high rate discharge [7,25]. Therefore, thermal management based on surface temperature measurement may lead to insufficient cooling, and measurement of the core temperature is critical. This may improve not only the effectiveness of thermal management but also electrochemical performance optimization of Li-ion batteries. For example, core temperature measurement of multiple cells in a battery pack may be used for load balancing within the pack by decreasing the load on an overheated cell.

Due to its importance in thermal control, a significant effort has been expended for measuring the core temperature in several other engineering systems. For example, in computer microprocessors, temperature sensors are embedded deep within the microprocessor chip where the highest temperature is expected to be encountered [26]. Similar core temperature measurement is also desirable for Li-ion cells. While the temperature on the surface of a Li-ion cell can be easily measured using thermocouples or other thermal sensors [7], measurement of the core temperature is not straight-forward. The electrochemically active environment inside a Li-ion cell presents challenges for the survival of any temperature sensor embedded within. Due to the hermetically sealed nature of the cell, connecting to an embedded sensor is also difficult. Thermocouples have been inserted in Li-ion cells [7,8,25,27], but this approach is unreliable and often causes cell failure. Some research has been carried out to utilize certain electrochemical characteristics of the cell as indicators of its temperature [28], but this approach only yields the volume-averaged temperature, and does not give information about the peak temperature at the core of the cell. The insertion of fiber Bragg sensors has also been investigated [29], however, this approach is expensive and cumbersome, and unlikely to be a candidate for implementation at a large scale. Non-invasive temperature measurement techniques such as ultrasonic temperature measurement – in which the speed of propagation of an ultrasonic wave through a device is used to determine the average temperature along the path [30] – have not been used for a Li-ion cell, possibly due to lack of data on speed of sound as a function of temperature in a Li-ion cell. Given the shortcomings of the current state-of-the-art, development of new, non-intrusive core temperature measurement techniques is very desirable for Li-ion cells. This is likely to have a direct impact not only on thermal management of the cell, but also on real-time performance optimization.

In the recent past, a transduction-free method for measurement of core temperature in a heat-generating cylinder based on measurement of surface temperature fields has been developed [31,32]. In this method, the steady-state [31] or transient [32] core temperature of the cylinder has been shown to be related to surface temperatures through appropriate space and time integrals. Accurate measurement of the core temperature based on non-invasive, infra-red (IR) measurement of the surface temperature field has been demonstrated. This method has the advantage of being non-intrusive and based entirely on the surface temperature, which is relatively easy to measure. Past papers [31,32] have demonstrated this method for non-electrochemical test cells in which heat is generated through Joule heating, a much simpler mechanism compared to active electrochemistry inside a Li-ion cell.

This paper presents non-invasive measurement of the core temperature of a 26650 Li-ion cell during high-rate discharge. The core temperature is determined using a theoretical model that utilizes measurements of the transient temperature field on the outside surface of the cell. Core temperature is measured in this manner for multiple discharge rates, and for a discharge process involving sudden change in discharge rate. In each case, good agreement is found with independent measurements of the core temperature using an embedded thermocouple. These experiments demonstrate an effective, non-invasive method for determining the core temperature of an operating Li-ion cell, which may be helpful for thermal control, performance optimization as well as monitoring of thermal runaway.

2. Theoretical model

A theoretical model to predict the core temperature of a heat-generating cylinder as a function of time based on measurements of the temperature field on the outside surface of the cylinder has been presented in a recent paper [32]. Fig. 1(a) shows a schematic of an infinite cylinder of radius R with volumetric heat generation $Q(t)$ occurring within. This model can be applied to a heat-generating, cylindrical Li-ion cell shown in Fig. 1(b), for which the core temperature $T_0(t)$ is of interest. The outside surface temperature of the cylinder, $T_{out}(\theta,t)$ is measured circumferentially and as a function of time. When the heat generation rate $Q(t)$ is known, it has been shown [32] that utilizing the measured outside temperature as a transient boundary condition, the governing energy conservation equations can be solved using the method of undetermined parameters. This has been shown [32] to result in the following expression for the core temperature $T_0(t)$

$$T_0(t) = T_{0,A}(t) + T_{0,B}(t) = \left[\frac{QR^2}{4k_r} + \sum_{n=1}^{\infty} u_n e^{-\alpha_r \mu_n^2 \cdot t}\right] + \sum_{n=1}^{\infty} v_{0n}(t) \tag{1}$$

where k_r and α_r are the thermal conductivity and thermal diffusivity respectively of the cylinder. The coefficients u_n and $v_{0n}(t)$ are given by

$$u_n = \frac{-\frac{Q}{4k_r}\int_0^R \left(R^2 - r^2\right) \cdot rJ_0(\mu_n r)dr}{N_{r,n}} \tag{2}$$

and,

$$v_{0n}(t) = \frac{\alpha_r \mu_n R J_1(\mu_n R)}{N_{r,n}} \int_0^t w_{0I}(\tau) \exp\left[-\alpha_r \mu_n^2 (t-\tau)\right] d\tau \tag{3}$$

In Eqs. (2) and (3), $\mu_n R$ are roots of J_0, the Bessel function of the first kind and order zero. The eigenfunction normalization integral $N_{r,n}$ is given by

$$N_{r,n} = \frac{R^2 J_1(\mu_n R)^2}{2} \tag{4}$$

Finally, $w_{0I}(\tau)$ is the circumferential integral of the outside temperature $T_{out}(\theta,\tau)$ at any time, given by

$$w_{0I}(\tau) = \frac{1}{2\pi}\int_0^{2\pi} T_{out}(\theta,\tau)\, d\theta \tag{5}$$

Note that when the heat generation rate Q is a function of time, the first term $T_{0,A}(t)$ in Eq. (1) must be replaced by

$$T_{0,A}(t) = L^{-1}\left[\frac{\alpha_r \bar{Q}}{s k_r}\left(1 - \frac{1}{I_0\left(\sqrt{\frac{s}{\alpha_r}}R\right)}\right)\right] \tag{6}$$

where L^{-1} is the inverse Laplace transform, $\overline{Q}$ is the Laplace transform of $Q(t)$, and I_0 refers to modified Bessel function of the first kind and of order zero. The Laplace transform $\overline{Q}$ can be determined once the expression for Q(t) is known, which may vary either smoothly or sharply with time.

Eq. (1) provides the basis for determining the core temperature of a Li-ion cell undergoing a discharge process that generates a cer-