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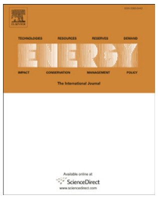

Measuring and assessing the effective in-plane thermal conductivity of lithium iron phosphate pouch cells

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ABSTRACT

The objective of this research is to experimentally determine the effective in-plane thermal conductivity of a lithium iron phosphate pouch cell. An experimental setup is designed to treat the battery cell as a straight rectangular fin in natural convection. Thermography and heat sensors were used to collect data that yields the temperature distribution and heat transfer rate of the fin, respectively. One-dimensional fin equations were combined with the experimental data to yield the in-plane thermal conductivity through an iterative process that best-fits the data to the model. The experiment was first calibrated using reference plates of different metals. The fin model predicts the thermal conductivity value well with a correction factor of approximately 7%–9%. Using this experimental method, the in-plane thermal conductivity of the pouch cells is measured at different state of charge (SOC) levels. The in-plane thermal conductivity decreases approximately 0.13 $\mathrm{Wm}^{-1}\,{}^{\circ}\mathrm{C}^{-1}$ per 10% increase in SOC for the LFP cells. This translates to a 4.2% overall decrease in the thermal conductivity as the cell becomes fully charged.

1. Introduction

Lithium iron phosphate (LFP) batteries are being chosen by an increasing number of automotive manufacturers to propel all types of electric vehicles (xEVs) [1,2]. However, one of the issues facing this particular electrochemistry is its comparatively high rate of heat generation [3–5].

Like all of the other lithium electro chemistries, the performance of a LFP battery begins to suffer once it is outside its optimum temperature range. Elevated cell temperatures can cause an increase in the side reactions of the chemical compounds within the cell. As a result, there is a safety concern of thermal runaway at high temperatures. Operating below the lower limit of the temperature range can cause sluggish electrochemical reactions and thus increase the internal resistance. One way to address these temperature-related shortcomings is to integrate a battery thermal management system (BTMS). A complete and accurate understanding of a cell's thermal behavior is crucial to designing a BTMS that will maximize its performance under all of the possible operating conditions [6–8]. Unfortunately, this behavior is a complex one. The thermal behavior of cell is comprised of several different heat sources that manifest through several different physical properties, one of which is thermal conductivity.

Thermal conductivity, k, is the intrinsic property of a material to conduct heat. The ability to do so depends on the availability of free electrons within the material and the degree to which it possesses a crystalline structure. Due to the layered construction of a pouch cell and the presence of chemical reactions, its effective thermal conductivity is highly orthotropic and thus requires a separate investigation for both the cross-plane (along the cell thickness) and in-plane (along the cell length) directions.

Techniques for precisely measuring cross-plane thermal conductivity are much more complex than they may initially appear. Care must be taken to ensure that heat flow is one-dimensional and accurately measured. The guarded hot plate technique (GHPT), represented by ASTM C177-04 [9] and ISO 8302:1991 [10], is probably the most commonly used thermal conductivity measurement method because the required materials are relatively inexpensive. However, this setup requires two test samples to be placed on either side of a film heater and the stack to be compressed. This ensures that the known heater output is evenly divided between the two samples. Not only is the heat input to each sample easily determined but it also acts as a plausibility check on the results. Another technique, represented by ASTM C518-10 [11] and ISO 8301:1991 [12], is a variant of the guarded hot plate and

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is commonly referred to as the heat flow meter. Here, the apparatus uses transducers to quantify the heat flow through a sample by applying a calibration constant to the transducer's electrical signals. The cross-plane thermal conductivity, k_z, (along the cell thickness) is usually found to be an order of magnitude less than the in-plane conductivity (k_x and k_y). This is mostly attributed to the high thermal conductivity of the current collectors and to a less extent to the orientation of particles in the electrode layers [13].

In a pouch cell, there also appears to be some influence of the SOC on its cross-plane thermal conductivity. Vertiz et al. studied this relationship on a 14 Ah LFP pouch cell [14]. They found that it reached a maximum value of 0.284 W $m^{-1}K^{-1}$ at 50% SOC level. This maximum was 16%–17% higher than what was measured at the extremes of 100% SOC and 0% SOC. In contrast, for a 14.5 Ah LFP pouch cell at room temperature, Bazinski and Wang [15] found the average cross-plane thermal conductivity to be slightly higher at 0.34 $Wm^{-1}K^{-1}$ at 50% SOC and that it steadily decreases as the SOC is increased.

The in-plane thermal conductivity of a pouch cell is rather difficult to measure. According to Vertiz et al. [14], in-plane thermal conductivity is not measureable using the hot plate standard procedure (ASTM C177-97) due to the impossibility of applying any heat to the cell side. Fortunately, there are some alternative methods available. Thermal Impedance Spectroscopy (TIS) for example uses heat pulses applied to the specimen surface [16]. Others calculate this property using the cell's internal structure and the thermal properties of each constituent material [14]. Teertstra et al. [17] measured the in-plane thermal conductivity of porous gas diffusion media in a proton exchange membrane fuel cell using a parallel thermal conductance technique. Here, a new experimental method is offered that treats the pouch cell as a cooling fin and does not require knowledge of its interior composition.

Fins are extended surfaces that operate as a combined conduction-convection heat system. Ideally, the design is one which offers a large surface area-to-volume ratio to maximize the heat transfer from a hot body to its surroundings. The geometry of the pouch cell is one that approaches this idealization. As such, it offers the opportunity to determine a thermo-physical property that is somewhat elusive through a novel experimental method that will be described in this paper.

Used in a myriad of applications, fins have become a well-studied topic in the field of heat transfer and may be found in texts solely dedicated to their understanding [18,19]. Much has also been published on determining the characteristics and performance parameters for many different fin shapes and boundary conditions [20–23].

The objective of this study is to apply the fin technique to experimentally determine the in-plane thermal conductivity of a pouch cell. This method is used to assess the effect of SOC on the effective in-plane thermal conductivity of the cell.

The remainder of this paper is divided into four sections. Section 2 will present the experimental setup and procedure. Section 3 will present the analytical equations used in the data analysis. Section 4 will present the results and discuss the outcome. Finally, Section 5 will offer the conclusions.

2. Experimental procedure

2.1. Experimental material-pouch cell

Two different Li-ion pouch cells were studied in this research as shown in Fig. 1. The first cell is a new 14.5 Ah lithium iron phosphate (LFP) pouch cell (Model F014) manufactured by EiG (South Korea). The cell has a graphite-coated negative electrode and a lithium iron phosphate positive electrode. The cell is encased in a laminated aluminum pouch. It has an operating temperature range of −30 °C to 50 °C and a specific energy of 100 Wh/kg. The cell specifications are listed in Table 1.

Fig. 1. Image of the 10 Ah LFP cell (left) and 14.5 Ah LFP cell (right).

The second test specimen is a commercially available 10 Ah LFP pouch cell (Model PL70122200LK). Manufactured by Amazing Energy Ltd. (China), the cell also has a graphite-coated negative electrode and is similar in size. Its cell specifications are also listed in Table 1. Cell thickness measurements for both test cells are taken at 50% SOC and it is assumed that any swelling or contraction due to SOC changes is negligible.

2.2. Test assembly

Fig. 2 shows the side view of the test assembly experiment set up where the pouch cell is treated as a rectangular fin as well as the coordinate system used. The tab end of the cell is the fin base, which is then placed between two heat exchangers. Both heat exchangers are plumbed in a parallel flow and supplies heat to the fin base from a common water bath. As shown in Fig. 3, a grouping of six thermo-electric-modules (TEMs) wired in series is placed between the heat exchangers and the base of test specimen to measure all heat transfer into the fin. Thermal interface grease (Dow Corning TC-5022) is applied to both faces of the TEM grouping prior to mounting on the plate. Besides reducing thermal contact resistance, it also aids in sensor adhesion. The tabs between the heat exchangers are surrounded with foam insulation to prevent unintended heat leakage. A T-type thermocouple is mounted to the reference plate that measures the base temperature of the fin. The assembly is then clamped between two heat exchanger plates by a

Table 1
Test cell specifications for 14.5 Ah LFP pouch.

Parameter	10 Ah	14.5 Ah
Height	200 mm	220 mm
Width	122 mm	140 mm
Thickness	7.2 mm	7 mm
Mass	350 g	385 g
Standard impedance	5 mΩ	8 mΩ
Maximum charge voltage	3.65 V	3.65 V
Nominal voltage	3.2 V	3.2 V
Minimum discharge voltage	2.0 V	2.0 V
Maximum continuous charge current	1C	1C
Recommended discharge current	Up to 10C	Up to 5C
Specific heat capacity	N/A	1.39 J g^{-1} °C^{-1}