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Surface temperature evolution and the location of maximum and average surface temperature of a lithium-ion pouch cell under variable load profiles.

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Abstract

This experimental work attempts to determine the surface temperature evolution of large (20 Ah-rated capacity) commercial Lithium-Ion pouch cells for the application of rechargeable energy storage of plug in hybrid electric vehicles and electric vehicles. The cathode of the cells is nickel, manganese and cobalt (NMC) based and the anode is graphite based. In order to measure the surface temperature, thermal infrared (IR) camera and contact thermocouples were used. A fairly uniform temperature distribution was observed over the cell surface in case of continuous charge and discharge up to 100A and the location of the maximum temperature was observed around the center region of the cell. On the other hand, during high current micro-pulse up to 80A, the temperature distribution was comparatively non-uniform. The location of the maximum and average temperature were observed around the positive tab of the cell and at the center region of the cell respectively.

Keywords: Electric Vehicle, Lithium Battery, Thermal Management, Modelling.

1 Introduction

In order to meet the increasing demands in terms of performance and of thermal safety of automotive Li-ion batteries, a high number of research works have been dedicated on thermal issues towards a better and safer li-ion battery [1-3]. It is well known that the heat generated within the cell due to the contribution of reversible heat (entropic heat components) and irreversible heat (ohmic and polarization resistance heat components) is one of the major concerns from the viewpoint of both the performance and thermal safety of a li-ion cell. Therefore, thermal modeling of the cell has proven to be a method of huge potential for the improvement of these issues relevant to the performance and thermal safety [4]. In fact, thermal behavior of not only a single cell but also of a battery module consisting several cells can be predicted with high accuracy through thermal modeling.

In reality, variation of cell surface temperature resulted from internal heat generation can be measured by different methods. The accuracy of the thermal model can be validated very effectively through comparing cell surface temperature obtained from the physical measurements with the result from the thermal model [5-6]. However, due to the complexity of electrochemical reactions inside the cell, the surface temperature distribution can be non-uniform over the cell surface [7, 9-10]. Thus among the different methods of measuring cell surface temperature, single point measurement (e.g. contact thermocouple) is not adequate to measure the spatially non-uniform temperature distribution. In this case, thermal infrared (IR) imaging is a potential method to observe and measure this spatially non-uniform temperature distribution with high accuracy.

Despite the high importance of cell surface temperature measurement, to authors' knowledge, very few works have been published dedicated to cell surface temperature measurements by using IR thermography; especially for high capacity large Li-ion NMC (Nickel, Manganese, Cobalt oxide based) pouch cell. In this work, the spatially non-uniform temperature distribution of a 20 Ah (rated capacity) NMC Li-ion cell under constant charge and discharge load up to 100A and high current micro pulses up to 80A were investigated by using IR camera. Additionally, high current micro-pulses were applied on the cell at different State of Charge (SoC) levels in order to investigate the dependence of the surface temperature variation on the SoC level.

Although temperature measurement by one or more thermocouples or thermistors is inadequate, these methods are often used to monitor cell surface temperature during characterization of large number of cells in order to avoid complexity in the test setup. Thus the knowledge of the location of the maximum and of the average temperature is crucial for the placement of the thermocouples or thermistors. Therefore, an analysis was also made on the IR images in order to find the locations of maximum and average cell surface temperature.

2 Experimental

Two different types of load profiles were applied on a commercial 20 Ah NMC Li-ion pouch cell. One type included continuous complete charge at 0.5 I_t[1] (10A) and 1I_t (20A) and complete discharge at 0.5 I_t (10A), 1 I_t (20A), 2 I_t (40A), 3 I_t (60A), 4 I_t (80A) and 5 I_t (100A). The other type included micro-pulse test at high current rates of 3 and 4 I_t. The charge and discharge limits were set with respect to the cell voltage. 4.2 V and 3 V were the end of charge and discharge voltages respectively. The micro-pulse consisted of short (2 sec) charge and discharge pulses and a rest time (2 sec) in between. A thermal IR camera (Fluke Ti25) were used to observe the spatial distribution of cell surface temperature. Additionally, four K type contact thermocouples (accuracy ± 2° C) were also used to record the cell surface temperature at specific locations. Figure 1 shows the relative position of the contact thermocouples TC1-TC4. In order to achieve accurate result from IR thermography, cells were placed in a nearly closed and dark environment (to avoid visible light interference). Moreover, cell surface was painted uniformly with a dull black paint.

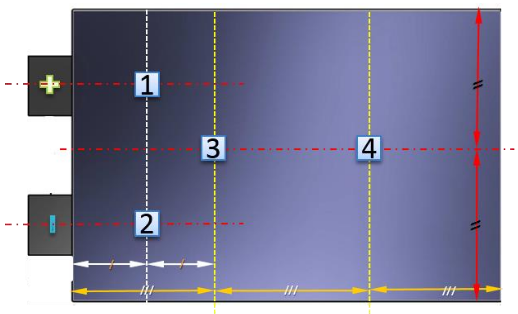

Figure 1: Relative positions of thermocouples (TC1-TC4) on the cell surface.

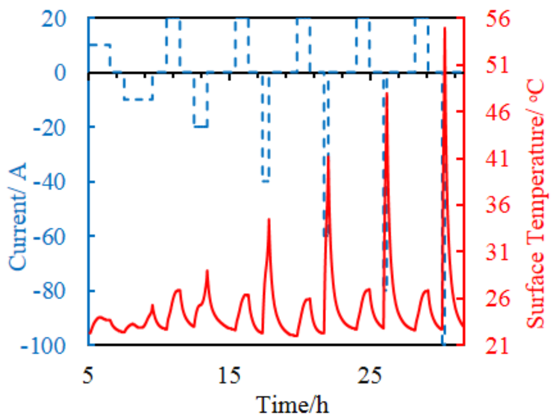

Figure 2: Thermocouple 1 (TC1) based temperature profile (solid red line) and corresponding load profile (dashed blue line) during continuous charge at 0.5 I_t and 1 I_t and discharge at 0.5 I_t, 1 I_t, 2 I_t, 3 I_t, 4 I_t and 5 I_t.

3 Results and Discussion

Figure 2 shows the thermocouple 1 (TC1) based temperature profile during complete charge at 0.5 I_t and 1 I_t and complete discharge at 0.5 I_t, 1 I_t, 2 I_t, 3 I_t, 4 I_t and 5 I_t respectively. Temperature profile during charging shows an initial rise until the state

[1] According to the IEC 61434 standard,
I_t= C/1h, where C is the discharge capacity of the cell in Ah.

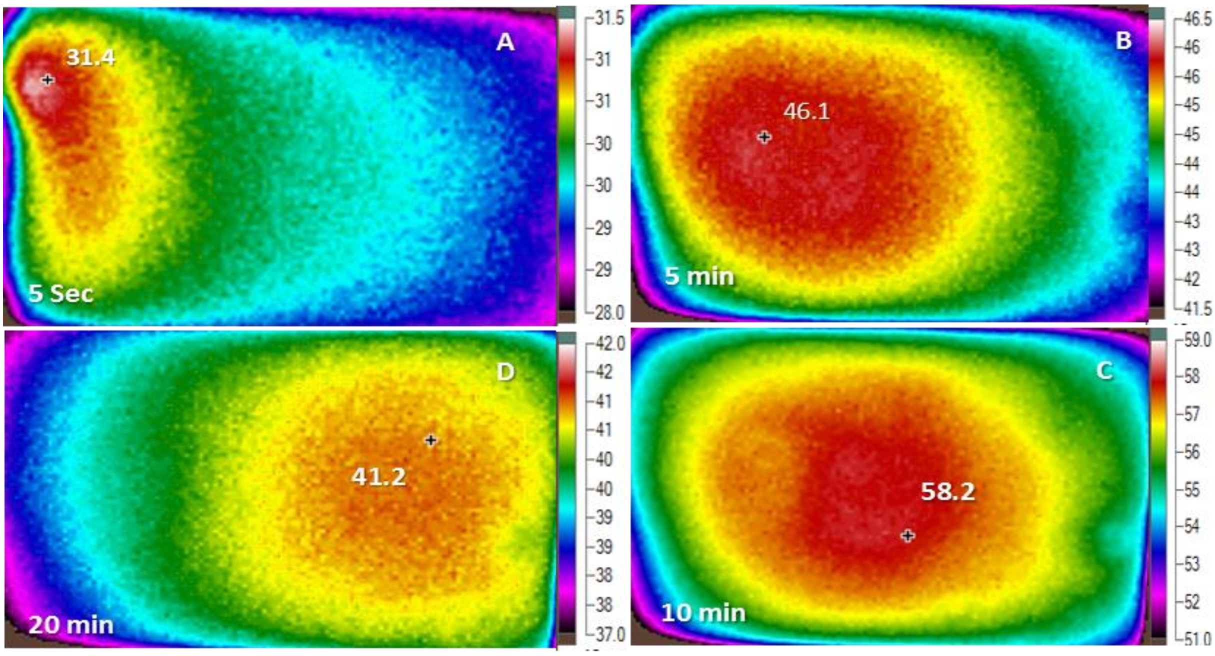

Figure 3: IR images during discharge at 5 I_t (100 amps); A) after 5 seconds, B) after 5 minutes, C) after 10 minutes, D) after 20 minutes (load disconnected). The Orientation the cell of the 4 images is according to Figure 1. Each Individual image shows the location of the respective maximum temperature.

of charge (SoC) level reaches approximately 50%. After that, the temperature remains fairly steady until it reaches 100% SoC (4.2 V). Discharge at different rates shows comparatively different temperature profile. For instance, during discharge at 0.5 I_t the temperature rises until ~70% SoC followed by a drop until it rises sharply again after it reaches ~30% SoC. In order to explain the phenomenon of temperature drop, one may consider the relative dominance of reversible and irreversible heat contributions. It was found that endothermic entropy change is the result of phase change in the electrode material at a certain SoC level range [8]. Both of the electrodes may undergo phase changes based on the ratio of lithium and other elements (e.g. Cobalt) at cathode and at anode the ratio of lithium and carbon during intercalation of lithium [8,10]. However, at higher current rate, the contribution of polarization resistance heat and ohmic resistance heat to the total heat generated within the cell becomes dominant. Therefore, temperature drop due to phase change became less significant at 1 I_t discharge. At higher current of 2 I_t and 3 I_t, this effect became trivial, shown by a slight change in the steepness (slop) of the temperature profile. At 4 I_t and 5 I_t rate the effect is negligible.

The IR images during discharge (Figure 3) at 5 I_t rate depicts the fairly uniform distribution of the cell surface temperature. It is clear from the temperature pattern of the IR images that- initially the most heated regions were at the adjacent areas of the tabs of the cell and slightly higher near the positive tab. This can be attributed to the higher resistance at the aluminium positive tab and current collector. However, this finding is inconsistent with the findings of Veth et. al., who observed that the maximum temperature was initially near the negative tab [10]. In order to explain this inconsistency, variation in commercial cell design (e.g. surface area of the tabs and current collectors) can be considered [11].

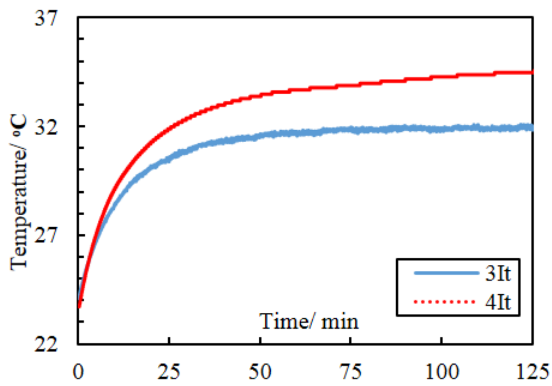

Figure 4: Temperature profiles during micro-pulse cycling at 3 I_t and 4 I_t

Nevertheless, with the progression of the discharge towards ending, the temperature distribution became more uniform over the whole surface of the cell (Figure 3B and Figure 3C) with the most heated region located at the centre region of the

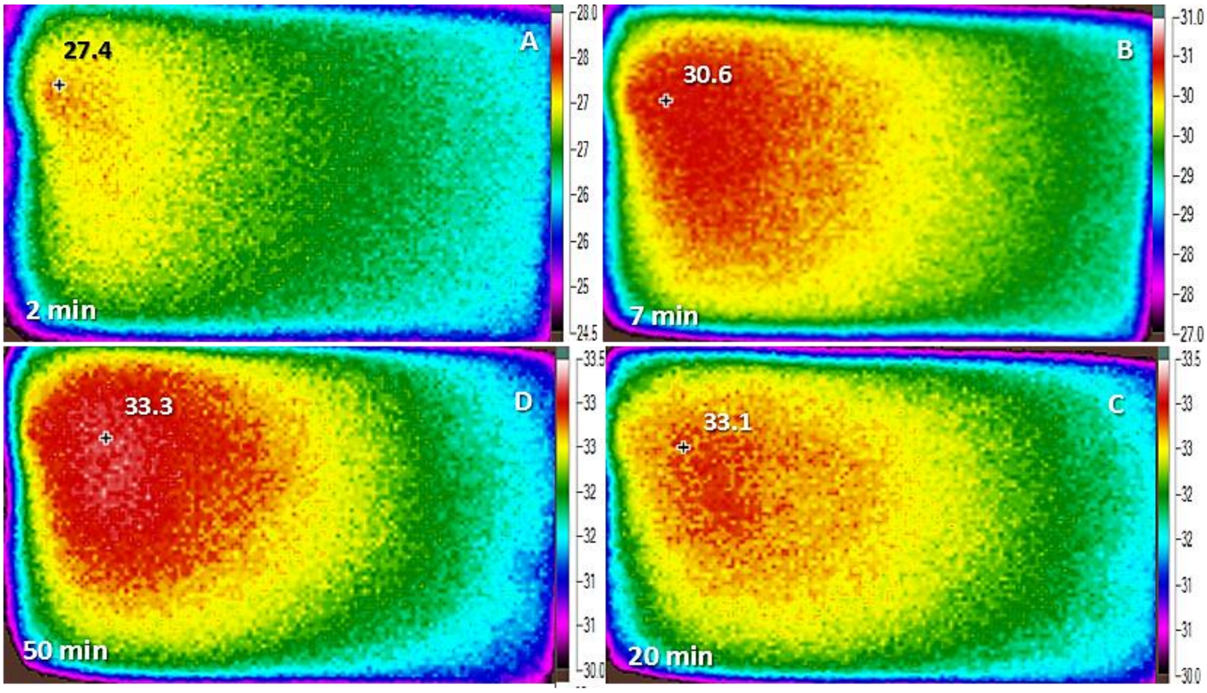

Figure 5: IR Images during micro-pulse cycling at 4 I_t; A) after 2 minutes, B) after 7 minutes, C) after 20 minutes, D) after 50 minutes. The orientation of the IR images is according to Figure 1 and individual images shows the location of the maximum temperature.

cell. Similar patterns were observed with charge and discharge at other I_t rates. Figure 3D shows the temperature distribution during heat dissipation (load was disconnected). This pattern suggests that the heat dissipation rate was higher at the upper half region of the cell (the half that contains the tabs) under natural heat transfer (at ambient temperature ~22 ^{o}C).

On the other hand, during the micro-pulse cycling, the temperature profile showed different behavior compared to the profile during continuous charge or discharge. Figure 4 shows the temperature profile obtained by TC1 over the period of the micro-pulse testing at 3 I_t and 4 I_t. At the beginning, the temperature rose sharply in both cases. Approximately after ~500 cycles or ~1 hour, the temperature reached a steady state condition (variation < 1° C per 5 minutes). According to the IR images (Figure 5), it is clear that, as the cell surface temperature proceeded towards steady state, the heat distribution over the surface became non-uniform. And the upper half portion of the cell, which is near to the tab, was comparatively hotter than the other half. It is also visible from the IR images that the hottest point is mostly located near the positive tab of the cell. Local high current density at the adjacent areas of the tab for very short time can be attributed for this localization of hottest region. In addition, micro-pulse cycling was performed on the cell at different SoC levels. Figure 6 shows that there is no significant dependence of temperature rise during micro-pulse cycling on SoC level of the cell. However, at SoC levels less than 30% and higher than 70% the temperature rises were comparatively higher which can be due to the dependence of cell internal resistance on SoC. The internal resistance is normally higher at the end of discharge process.

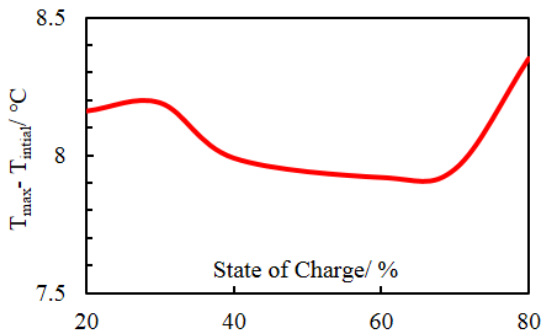

Figure 6: Temperature rise during micro-cycle pulse at 3 I_t and at different SoC levels.

While the position of the hottest point remains approximately constant over the period of the operation (micro-pulse cycling), the position of the average temperature point varies. In order to determine the position of the average temperature point, a dedicated method of analysing the IR images was adopted. In this method, at first, two lines (line 1 and line 2) were drawn on every IR images of the cell surface dividing the cell surface into four equal segments as shown in Figure 7. After that, a rectangular box of 1cm × 1cm (real scale of the cell) were drawn 4 cm distant from the point of intersection of line1 and line2, denoted by Avg. Temp. Box (ATBox) in the figure. Maximum, minimum and average temperature of the area enclosed by ATBox were recorded and compared with global maximum and average temperature of the cell surface. Figure 8 and Figure 9 show the comparison of the average temperature of ATBox with the global maximum and average temperature during constant discharge and micro-pulse cycling respectively.

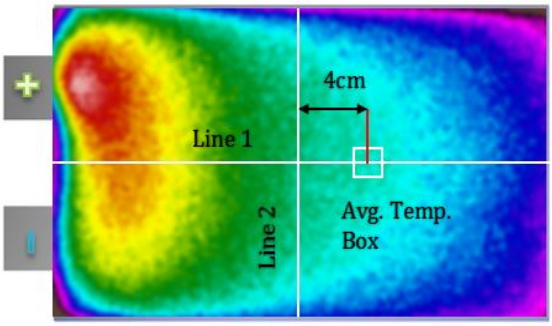

Figure 7: Method of analyzing IR images in order to determine the position of maximum and average temperature of the cell surface.

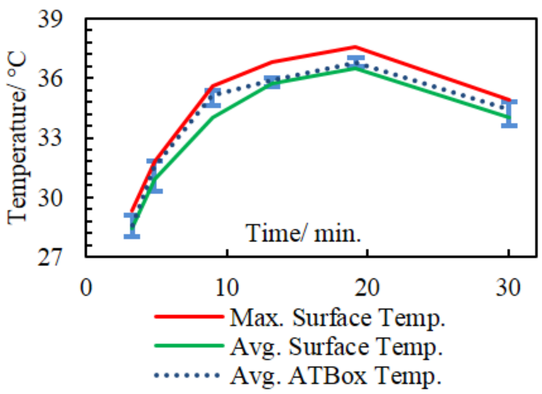

Figure 8: Comparison of ATBox temperature with global maximum and average temperature of cell surface during continuous discharging at 3 I_t.

During continuous discharge, although initially it showed a deviation of more than 1 °C, at critical stage (most heated) the ATBox temperature can fairly represent the global average temperature of the whole cell. On the other hand, during micro pulse cycling, the ATBox temperature can represent the global average temperature with high accuracy at any point. This findings can be exploited to measure cell average temperature by placing thermocouples/thermistors at the position of ATBox where the use of IR camera is rather complex. The same approach can be applied when interested in the global maximum temperature of the whole cell by placing the thermocouples/thermistor at the mentioned hottest point.

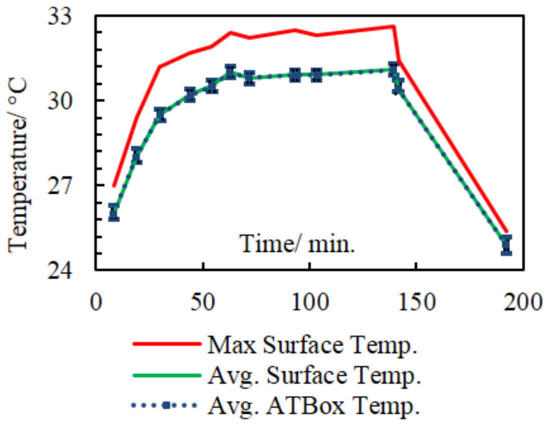

Figure 9: Comparison of ATBox temperature with global maximum and average temperature of cell surface during micro-pulse cycling at 3 I_t.

4 Conclusion

Cell surface temperature distribution under high current continuous charge and discharge along with high current micro-pulse cycling was studied by using contact thermocouples and infrared images. During continuous charge and discharge up to 100A, the temperature distribution was more uniform compared to the distribution during micro-pulse cycling. Maximum temperature was observed near the positive tab of the cell during micro-pulse cycling. While during continuous charge and discharge the position of the maximum temperature was observed around the centre region of the cell. A rectangular area of 1cm by 1cm on the cell surface, which can fairly represent the average surface temperature, was identified through data analysis obtained from IR images. The dependence of the surface temperature on the SoC level of the cell was also investigated and found that the surface temperature does not significantly depends on the SoC level of the cell.

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