

Lithium-ion Batteries – Analysis of Non-uniformity of Surface Temperature of Commercial Cells under Realistic Driving Cycles

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Summary

In this work, large format commercial li-ion pouch cells of two different chemistries and capacities were studied under realistic EV driving profiles in order to determine the non-uniformity of the cell surface temperature by using high resolution infrared thermography. A comparison of the surface temperature behavior was made under continuous constant current charge-discharge current profile. A 1-dimensional electro-thermal model was developed based on an equivalent circuit with RC elements. The simulation results were validated by obtained experimental result to predict the behavior of the cells.

Keywords: lithium-battery, battery model, thermal management, drive, discharge rate.

1 Background

The heating of li-ion cells is a well-known characteristic which raises safety concerns [1], [2]. In order to maintain the viability of the applicability in Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV), the safety requirement must be met by designing safer battery cell and efficient thermal management. In this regard, the knowledge of the thermal behavior and predicting the behavior during operation is undoubtedly very crucial [3]. Surface temperature study can play an important role in order to build an accurate model and for the prediction of cell surface temperature. In our previous work, it was shown that surface temperature distribution of li-ion battery cells is spatially non-uniform [4], [5]. And the pattern of this non-uniformity varies from one type of cell to another and depends on the type of load profile applied. For instance, high constant current (100 A) continuous discharge of a 20 Ah NMC (Nickel, Manganese, Cobalt oxide) pouch cell showed a different thermal behavior than in the case of dynamic charge/discharge micro pulse cycling. To the authors' knowledge, there are no reports of dedicated studies on spatial heating behavior of battery cells under realistic driving load profile, which can be very important in order to improve design of battery cells based on thermal behavior during real life operation. Moreover, existing electro-thermal models are, to our knowledge, mostly validated under continuous charge-discharge load [1], [6]. This can be less effective in predicting the thermal behavior in real life applications considering the non-uniformity of surface temperature.

In this work, a synthetic current profile was created based on WLTC class 3 speed driving cycle. This current profile was applied on two different lithium ion commercial cells. One is EIG NMC (Nickel, Manganese, Cobalt oxide) with rated capacity of 20 Ah and another is EIG LFP (Iron Phosphate) with rated capacity of 14 Ah. The spatially non-uniform surface temperature was recorded by an infrared camera.

Several regions on the cell surface were selected and detailed analyses of the temperature evolution of those region were made. A comparison was also presented between the surface temperature non-uniformity during the application of dynamic current profile and continuous charge-discharge current profile. A 1-dimensional electro-thermal model was developed. Simulation result and experimental result obtained from IR measurement were compared and herewith the electro-thermal model was validated.

2 Experimental procedures

2.1 Current Profile

A synthetic current profile was tailored from realistic driving profile and applied on the battery cells. The current profile was derived from class 3 worldwide-harmonized light vehicle testing cycle (WLTC). Figure 1a shows a WLTC driving cycle consisting 4 segments, low, medium, high and extra-high speeds [7]. In order to obtain a sufficiently stressful profile (from thermal point of view) for the battery cells, a specific segment was chosen as shown in the figure 1b to be converted into current profile. This segment consisted of a portion of medium speed segment and both the complete high and extra high segments.

The conversion from speed profile to current profile was performed according to the general propulsion equation as follows.

$$I = \frac{\frac{1}{2} \rho \cdot S \cdot C_x \cdot v^3 + C_R \cdot m_t \cdot g \cdot v + m_t \cdot a \cdot v}{\eta_{\text{motor}} \cdot \eta_{\text{cont}} \cdot \eta_{\text{conv}} V} \quad (1)$$

Significance of the symbols and respective assumed values for the conversion are listed in the Table1.

Table 1: Significance and values of the parameter of propulsion equation

Symbols	Significance, Unit	Assumed Values
ρ	Density of air, kg.m ⁻³	1.204
S	Frontal area of a car, m ²	2.09
C_x	Drag coefficient	0.32
C_R	Rolling coefficient	0.01
m_t	Total mass of the car, kg	1495
v	Speed of the car, ms ⁻¹	-
g	Gravitational acceleration, ms ⁻²	9.81
η_{motor}	Efficiency of motor, %	90
η_{cont}	Efficiency of the controller, %	90
η_{conv}	Efficiency of the converter, %	95
V	Voltage of battery pack, V	365

The resulted current profile was further modified to make it more stressful for the battery cell. All the rest periods (zero current) have been excluded from the profile. The final synthetic current profile is shown in Figure 1b. The duration of one such cycle is ~14 min representing a continuous driving without interruption. Maximum recharge current of the profile is ~60 A and maximum discharge current is ~80 A. At the beginning of the current profile there are few a high current recharge and discharge (~ 0-3 minute), followed by few low current discharges (3-7 minute) and finally some long and high current discharge (~7-14 minute). During implementation of the profile, the cells were charged completely to their respective maximum voltage. Followed by a discharge of 10% based on actual capacity of the cells in order to reach 90% state of charge (SoC). After this, a rest period was implemented to allow sufficient heat dissipation of the cells. Once the cells were at room temperature, the synthetic current profile was applied. The ~14 min cycles were repeated until the cells reached their respective lower voltage limit. A complete current profile consisting of several cycles can be seen in Figure 4. All the tests were performed by using an 80 channels battery tester (ACT 0550 type from PEC®, Leuven, Belgium).

2.2 IR Imaging

During the application of the current profile, the surface temperature of the cells was recorded by an infrared (IR) camera (A655sc type from FLIR®, USA). In order to avoid interference from reflected heat, the surface of the cells were painted uniformly with dull black paint. The complete setup was placed in a semi-closed environment to allow natural heat dissipation. Moreover, the camera was placed in way that the body of the camera makes an angle of $\sim 45^\circ$ with the vertical axis. A NTC 5K thermistor was attached to the bottom surface of the cells for simultaneous measurement and comparison with the measurement from the IR camera. The IR camera was calibrated by the manufacturer within the range $-40 - 150^\circ\text{C}$, with a maximum error of $\pm 2\%$. The thermal sensitivity, noise-equivalent temperature difference (NETD) of the camera is less than 30 mK. For the calibration of the camera measurement, emissivity correction was performed by measuring a known uniform surface temperature painted with the same dull black paint as used on the cell surface. Emissivity was set to ~ 0.98 .

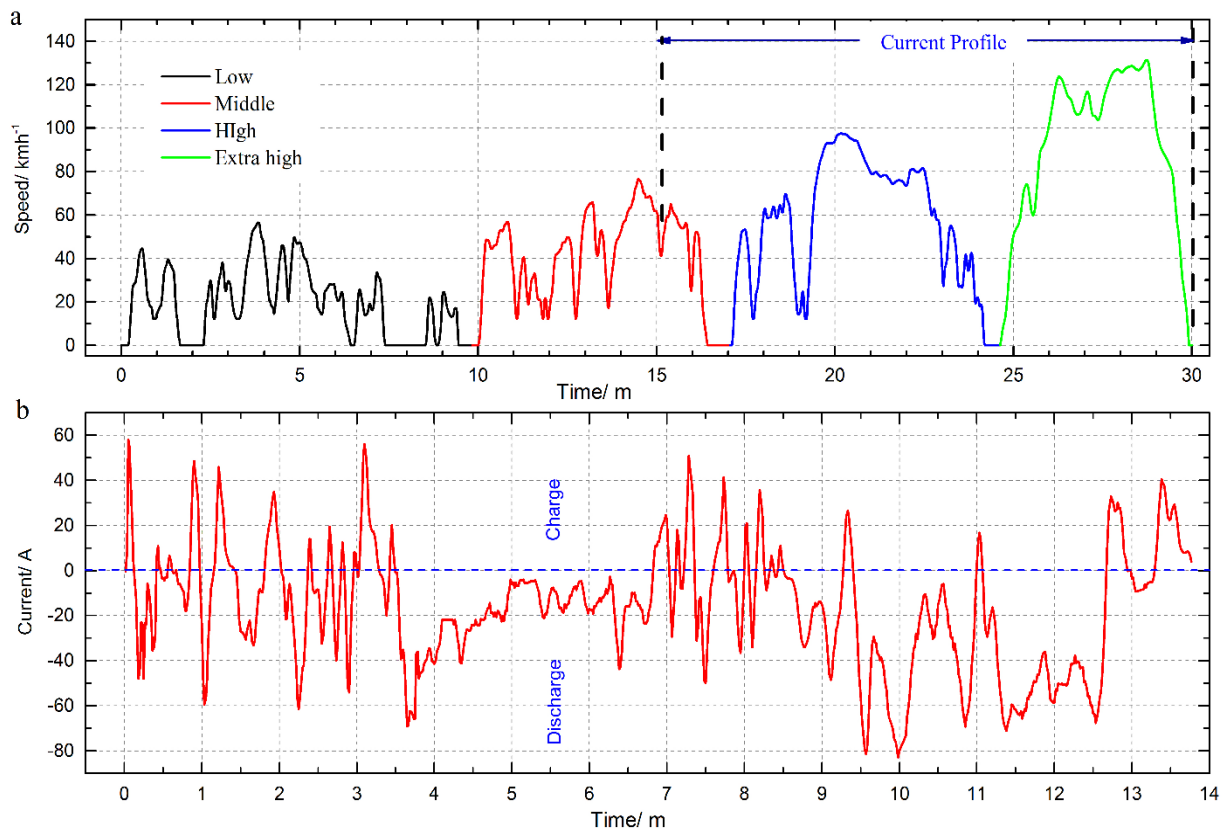


Figure 1: a) WLTC class 3 speed profile consisting 4 segments according speed level. A portion of the complete profile chosen for current profile is marked. b) Converted current profile from chosen portion of WLTC speed profile.

2.3 Cell Characteristics

Error! Reference source not found. shows the geometrical and electrical properties of the two selected types of li-ion cells, EIG NMC 20 Ah and LFP 14 Ah cell. The two cells are of two different cathode chemistries but both have graphitic carbon anode. Other important parameters for the cells can be obtained from available literature [8], [9]. Internal resistance values of the two cells were measured by means of the standardized hybrid pulse power capability (HPPC) test. The pulse currents for this HPPC test, for both type of the cells, were 20, 40, 60, 80, and 100 A. The pulses were performed at three different SoC levels, namely at 80%, 50%, and 20% SoC level. Figure 2 shows the internal resistance trend for the two cells. From the figure, it is evident that in the case of discharge pulse, and for all two chemistries, a higher internal resistance is observed at a low state of charge of the cell. Further, the lowest internal resistance is observed at a high state of charge, in combination with the higher current values. The LFP cells have comparatively higher internal resistance, which is also evident from their AC impedance values (Table1).

Table 2: Mechanical and electrical properties of the NMC and LFP Cells (collected from manufacturer product datasheet)

Properties		NMC	LFP
Geometrical			
Body	Length, mm	217	216
	Width, mm	130	130
	Thickness, mm	7.1	7.1
	Weight, g	428	380
Tab	Length, mm		
	Width, mm		
Electrical			
Nominal Voltage, V		3.65	3.2
Nominal Capacity, Ah		20	14
End of Charge Voltage, V		4.2	3.65
End of Discharge Voltage, V		3	2
Ac Impedance (1 KHz), mΩ		< 3	< 5
Specific energy, Wh/kg		174	120
Energy Density, Wh/L		370	230
Specific Power (DoD 50%, 10 Sec)		2300	2500
Power Density (DoD 50%, 10 Sec)		4600	4500
Maximum Charge Current, A		-	-
Maximum Discharge Current, A		100	140

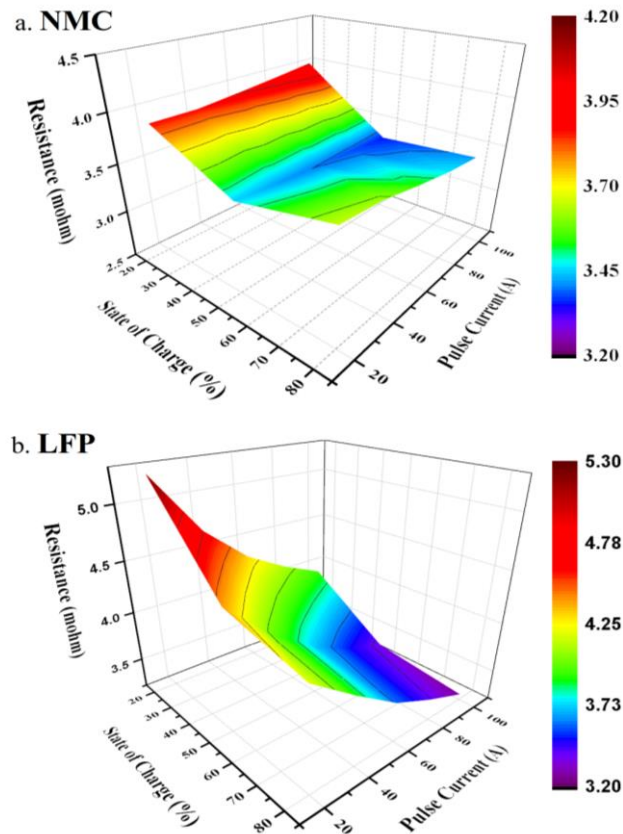


Figure 2: Internal resistances measured by HPPC test at an 80%, 50% and 20% SoC level with pulse currents of 20, 40, 60, 80, 100 A of (a) NMC discharge pulses; (b) LFP discharge pulses

3 Non-uniformity of surface temperature

3.1 NMC cell

Three important regions were selected on the surface of the pouch cells for in-depth analysis of the infrared images recorded during the test procedure. Figure 3 shows the location of 3 rectangles of size 1 cm × 1.5 cm. The red box near the positive tab is the “PosTab Box”, the blue box at the centre of the cell is the “Center Box”, and the black box at lower center of the cell is the “LowEnd Box”. The boundary drawn in green will refer to the complete surface.

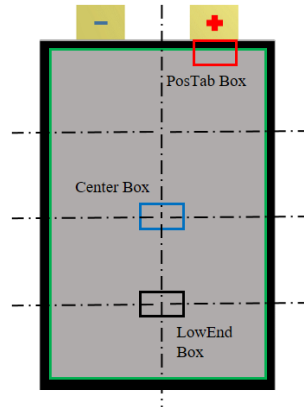


Figure 3: Schematic of a NMC cell with the location of 4 selected regions for in depth analysis of IR images.

In the case of the NMC cell, between the SoC window of 90% to 0% SoC (i.e. 3V), the synthetic current profile was repeated 4 times continuously without any break in between. Figure 4 shows the complete profile. Four repeated cycles are marked by C1-C4. A portion of the complete profile is enlarged in the figure also. IR images were recorded throughout the procedure at a frame rate of 1 Hz. Later, maximum temperature of the enclosed area by the selected boxes was plotted. Figure 5 shows the profile of the maximum temperatures obtained from individual IR images at every second. Some of the IR images are presented in Figure 6. Timing of the individual IR images are shown in Figure 4 and Figure 5. Figure 5 by a, b, c, d and e.

It is clear from the temperature profiles of Figure 5, for each cycles (C1-C4), the temperature reaches its maximum at the end of the cycle. Therefore, 4 peaks can be seen for 4 cycles. At the first cycle, temperature rise can be divided into three subsections according to the slope of the temperature rising. This is directly related to the intensity of the current of each cycle (as described in section 2.1 and Figure 1). First segment (0-3 minute) comprises more number of recharges than discharges and the discharges are of comparatively lower amplitude (maximum ~60 A). The middle segment comprises mainly discharges but of low amplitude. Thus the slope of the rising temperature profile is slightly reduced. As the final segment consists of high current discharges, the temperature showed a rapid rise until it reaches the peak at the end of first cycle. At the beginning of the second cycle, the temperature declined as the total heat dissipation at the first and middle segments dominated the total heat generation. At the final segment the temperature rises again until the peak at the end of the cycle. Rest of the cycles followed the same pattern. If the rise of the temperature during the last segment of each cycle are considered, with progression of cycles, temperature rise increases cycle to cycle. For instance, total rise during the final segment of first cycle is <3 °C while the respective rises are ~3 °C, ~4 °C and ~5 °C during the final segment of 2nd, 3rd and 4th cycle. This phenomenon can be explained by the increasing internal resistance with decreasing SoC level.

Regarding the spatial heat distribution and evolution over time, maximum temperature over the complete surface, Center Box and LowEnd box showed a similar behaviour. Moreover, the differences between the maximum temperatures of these three regions are insignificant over the complete profile. However, the maximum temperature of the region enclosed by PosTab box showed a slightly different evolution. During a high discharge pulse of the cycle, temperature showed spikes for a very short time (~5 sec). This is also evident in the IR images (Figure 6a and 6b). This IR images were taken during the 3rd cycle. At point “a” and point “b”, there are two high current discharge pulses (~80 A). Due to the high current distribution near the positive tab in combination with low electrical conductivity of aluminum tab gave rise to the heat generation in this region. This is in-line with our previous findings [4], [5]. According to our previous

findings, during high constant current continuous discharge, initially the most heated region was observed near the positive tab and with progression of discharge (lower SOC) most heated region shifted to the centre of the cell. But during high current micropulse application, the heated region remained near the positive tab.

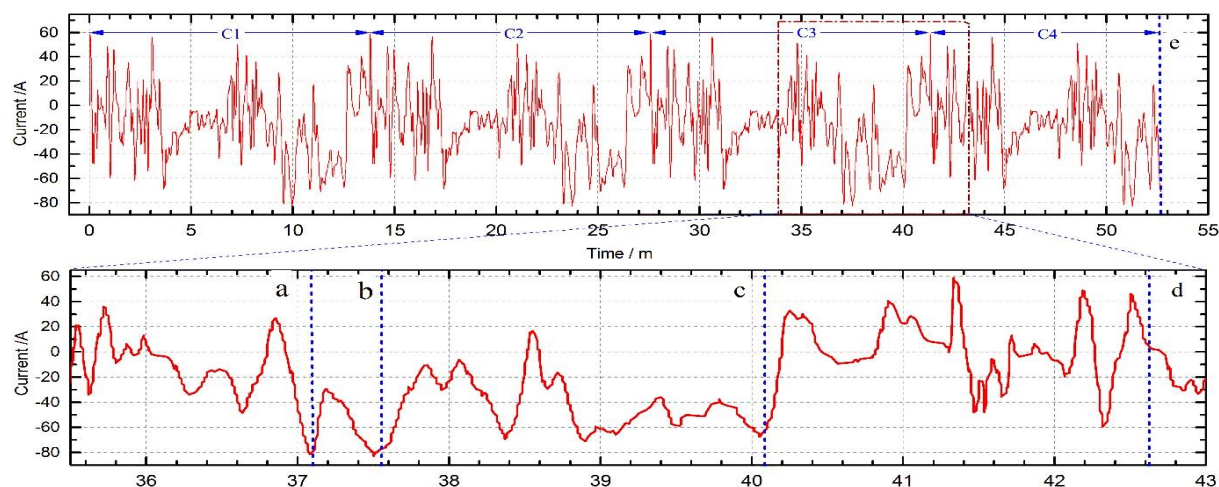


Figure 4: Complete current profile consists of 4 cycles of synthetic WLTC profile. A portion of the complete profile is enlarged. Some infrared images are presented in figure. a, b, c, d, e are the points corresponds to the IR images.

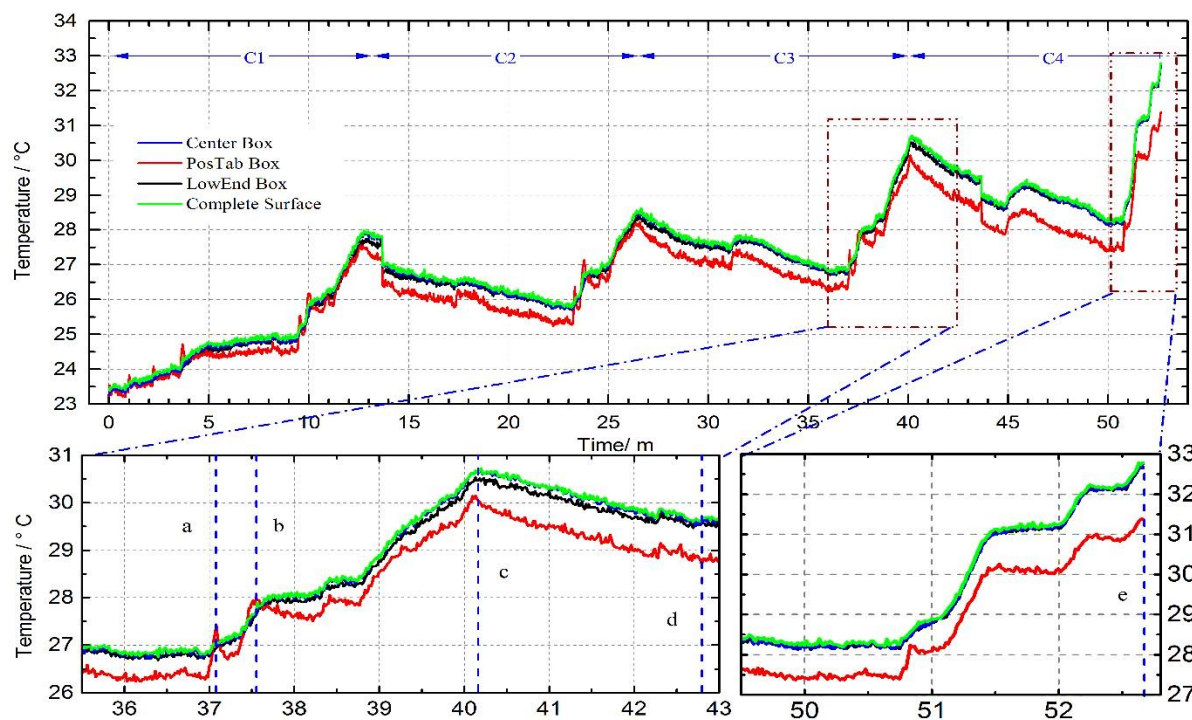


Figure 5: Profiles of maximum temperature of the region enclosed by the boxes. C1-C4 denotes individual WLTC synthetic current profile. Two portions of the profile are enlarged below showing the corresponding position of IR images of Figure 6.

Although during a single high current discharge pulse of the WLTC based synthetic current profile, the “PosTab Box” represents the most heated region, the temperature reduces immediately after the pulse. For this reason, at the very beginning of the rising part (final segment of a cycle) of the temperature profile (Figure 5), the difference between the maximum temperature of “PosTab Box” and the maximum temperature of “Center Box”, “LowEnd Box” and complete surface are insignificant (Figure 6a and 6b). This difference increased with the progression until the temperature reaches the peak of that particular cycle (Figure 6c). After that, this difference further increased (Figure 6d) with progression of time. Figure 6e shows the IR image at the end of 4th cycle, showing the most heated region in the centre and lower

centre area of the cell. It can be concluded that the temperature evolution during this synthetic WLTC profile shows similar behaviour to the temperature evolution during continuous constant current discharge.

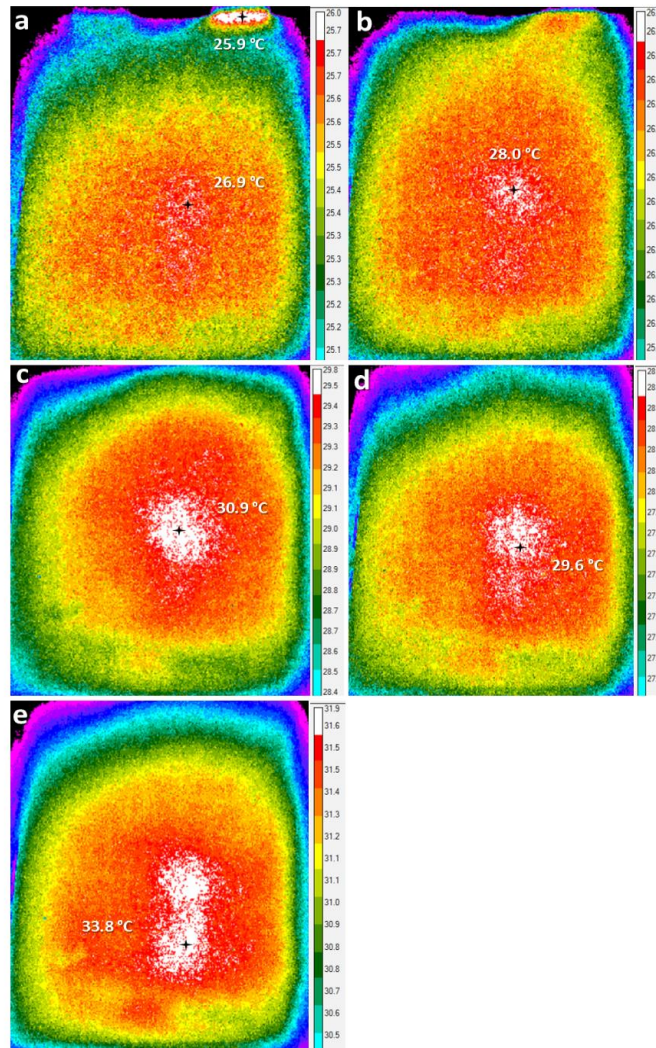


Figure 6: IR images of NMC 20 Ah Cell. Position of the individual images in terms time and current are demonstrated by a, b, c, d, e in Figure 4 4 and Figure 5. Maximum temperatures of the individual images are shown.

3.2 LFP cell

The same current profile was applied on a LFP 14 Ah cell as in case of the NMC cell. Surface temperature evolution was recorded by an IR camera in the same way as in the case of the NMC cell. For the analysis, a similar approach was taken by selecting 3 rectangular region on the surface of the cell (Figure 7). Important to mention, the location of the positive tab of the LFP cell is on the left side unlike the in the NMC cell schematic and IR images.

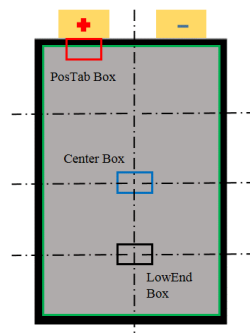


Figure 7: Schematic of a LFP 20 Ah cell with the location of 4 selected regions for in depth analysis of IR images.

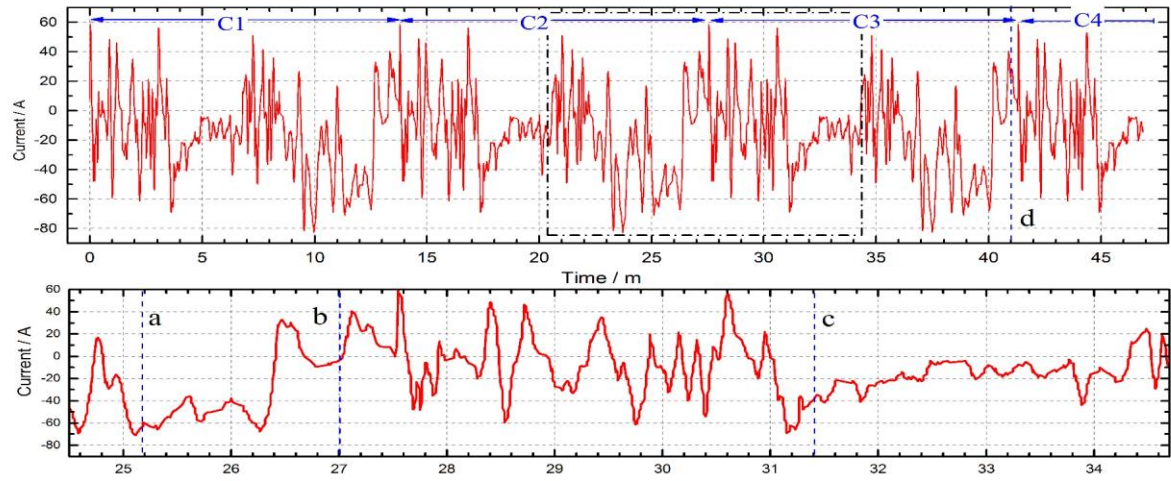


Figure 8: Complete current profile consists of 3 complete cycles of synthetic WLTC profile and a portion of 4th cycle. A portion of the complete profile is enlarged. Some infrared images are presented in figure. a, b, c, d, e are the points corresponds to the IR images of Figure 10.

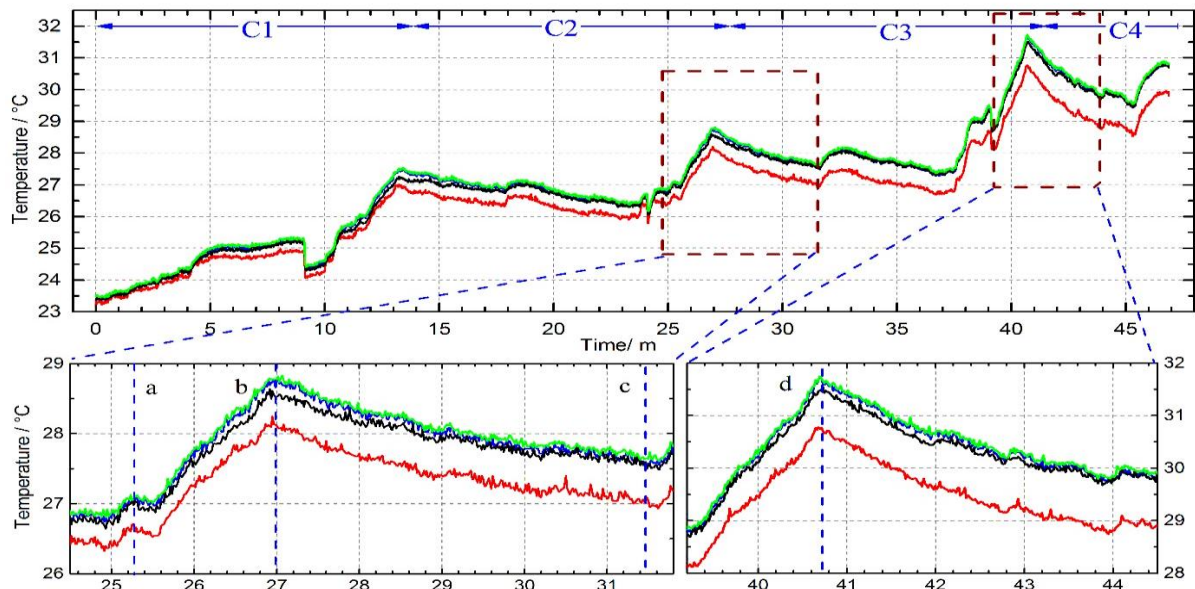


Figure 9: Profiles of maximum temperature of the region enclosed by the boxes. C1-C4 denotes individual WLTC synthetic current profile. Two portions of the profile are enlarged below showing the corresponding position of IR images of Figure 6.

Within the SoC window of 90% to 0% (2 V), the WLTC based synthetic current profile, 3 full cycles and a portion of 4th cycle could be performed. Figure 8 shows the complete current profile and also a portion of the complete profile is enlarged. Figure 9 shows the temperature profile along with the relative position of cycles. As only 3 cycles were performed completely, only 3 peaks can be seen in the current profile. Temperature profile for all the regions (Complete, Center Box, LowEnd Box and PosTab Box) showed a similar trend as in case of NMC cell. For instance, during the 1st cycle, 3 different slopes in temperature rise profile can be distinguished. And during the 3rd cycle, the temperature decreased until the final segment was reached due to dominant heat dissipation. The region near positive was heated during high current discharge pulses (figure 10a). However, it never surpassed the temperature of the center region of the cell throughout the complete profile. The most heated region always remained at the centre region (Figure 10b-10d). This suggests a better design of the LFP cell, in particular with regard to the tab size. How the design of the tab influences the thermal performance of cell can be found in literature [10]. The tabs of the LFP cells are broader than the tabs of NMC cell. Which might cause comparatively inferior current density in LFP cells near the positive tab area. Our previous study showed that in case of the LFP 14 Ah cell, the most heated region during high current constant discharge and during high current micropulse remained mostly

at the center of the cell. Now during a dynamic high current profile the cell showed similar temperature evolution.

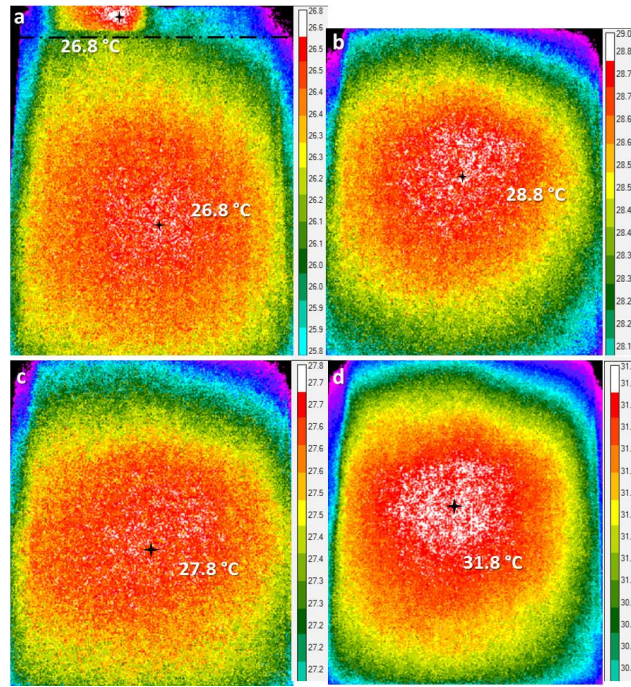


Figure 10: IR images of LFP 14 Ah Cell. Position of the individual images in terms time and current are demonstrated by a, b, c, d, e in Figure 8 and Figure 9. Maximum temperature of the individual images is also shown.

4 Electro-thermal model

An electro-thermal model was built for NMC li-ion cell based on equivalent circuit method (ECM) in Matlab® and Simulink®. Two RC element were used to build a dual polarization model [11]. Figure 11a shows the structure of the equivalent circuit. In the circuit, η (V) represent the voltage drops across different elements. And simulated voltage is calculated based on the following equation-

$$U = OCV + \eta_{\Omega} + \eta_{d1} + \eta_{d2} \quad (2)$$

The open circuit voltage (OCV) of the cell was measured by first fully charging the cell until 100% SOC (making use of a standardised charge protocol) and afterwards was discharged (Ah-based) to different predefined SoC levels based on actual capacity of the cell at 25 °C. OCV at each SoC level was measured after 3 hours rest (no current). Internal resistances were determined by HPPC tests. Figure 12 shows experimental voltage response and simulated voltage during the synthetic – WLTC based - current profile. It is clear from the figure the model can fairly predict the voltage response during a dynamic current profile. Even at high SoC level (90%) the simulated voltage is well in agreement with the experimental voltage response.

For simplification, the model was primarily built to predict the average temperature over the surface of a cell. Thus, it was assumed that the surface temperature is spatially invariable. The governing equation of the thermal model is based on the conservation of energy:

$$mC_p \frac{dT}{dt} = Q_{irrev} + Q_{rev} + Q_{transf} \quad (3)$$

where m is the cell mass (kg), C_p the heat capacity (J/kg/K), T is the cell surface temperature (K). The heat sources are divided in three parts, The irreversible ohmic heat (Q_{irrev}) generated by cell resistances, the reversible heat (Q_{rev}) due to electrochemical dynamics within the cell and finally the heat loss through convection (Q_{transf}) to the surrounding air.

The heat source can be calculated by the following three equations:

$$Q_{irev} = \left[R_{discharge} I^2 + R_1 \left(I - C_1 \frac{d\eta_{d1}}{dt} \right)^2 + R_2 \left(I - C_2 \frac{d\eta_{d2}}{dt} \right)^2 \right] \quad (4)$$

$$Q_{rev} = IT \frac{\partial OCV}{\partial T} (SoC) \quad (5)$$

$$Q_{transf} = hS (T_{amb} - T) \quad (6)$$

Where: h is the convection transfer coefficient (W/m^2), S is the battery contact surface area (m^2) with surrounding air at T_{amb} (K) temperature. $\frac{\partial OCV}{\partial T}$ is known as entropic heat coefficient. The entropic heat coefficient of NMC cell was determined by performing OCV measurements at different temperatures (25-45 °C).

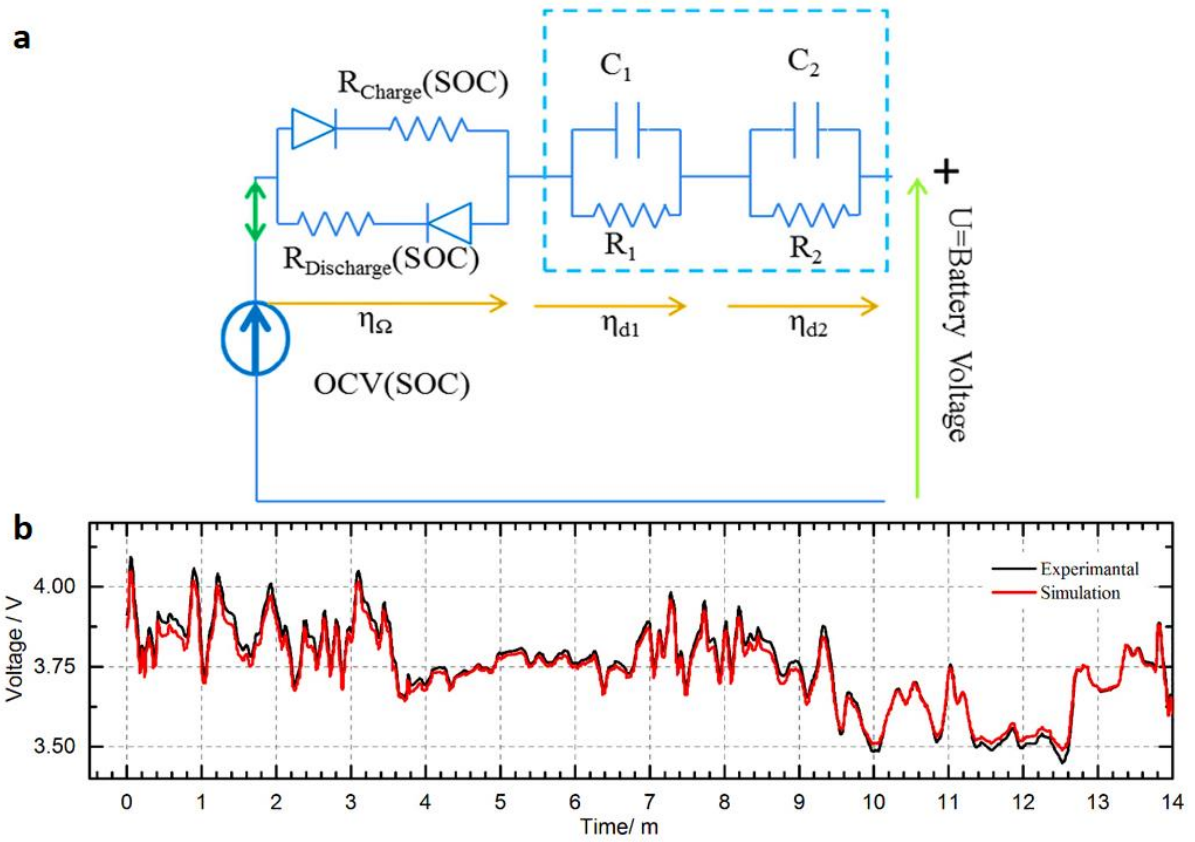


Figure 11: a) Structure of the equivalent circuit with two RC elements [11], b) Comparison of experimental and simulated voltage response.

Figure 12 shows the simulation result from the electro-thermal model along with the average temperature of the surface of the cell measured by IR camera. It can be said that this model can predict the average temperature of the cell with high accuracy (difference $\sim 0.5^{\circ}C$). The accuracy is slightly lower at low SoC level due to non-linear behavior of the cell at low SoC level. However, the difference between the simulated and experimental result is less than $1^{\circ}C$, even at low SoC level.

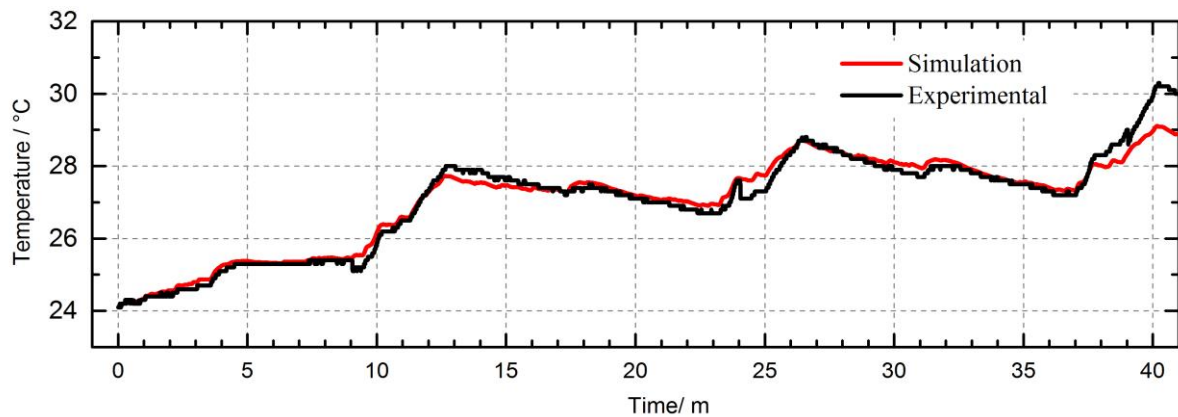


Figure 12: Simulated and experimental result of average surface temperature

5 Conclusion and future work

Knowledge of the surface temperature evolution of li-ion battery cells during realistic current profile is crucial. Here, we have created a realistic current profile for a single cell based on WLTC class 3-speed profile. This synthetic current profile was applied on two types of commercial li-ion cells, NMC 20 Ah and LFP 14 Ah. Temperature evolution was recorded and analyzed. It was found that the temperature evolution for this realistic current profile shows similar pattern as for constant current discharge. During high current discharge, which is the representative of high acceleration in the real world, the positive tabs get heated but for very short time. As the time progresses, the heat dissipation becomes more dominant. The most heated region is mostly located at the center and lower center (opposite to the tabs) of the cell. This behavior was also observed in both types of the li-ion battery cell. A 1-D electro-thermal model with two RC elements was built. Obtained simulation results are in good agreement with the experimental result. The model can predict the average temperature of the cell surface with good accuracy (error of less than 1°C). Although the model accuracy in predicting the average temperature is rather good, the 1D model cannot predict the maximum temperature evolution of the cell surface. Thus in the future work a 3D model will be built to predict the surface temperature evolution.

Acknowledgments

This research has been made possible, thanks to the research project “Battle” which was funded by the Flemish Agency for Innovation by Science and Technology (grant number: IWT130019). Further, we acknowledge Flanders Make for the support to our research team.

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Alexandros Nikolian graduated at the Reading University in the UK as Renewable Energy Engineer. He has experience in vehicle simulation & emissions, developed during his activities in the Joint Research Center of the European Union and Hexagon Studio in Turkey. He started as a PhD student in January 2014 at VUB mainly working on IWT BATTLE project and battery modelling



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