Surface Temperature evolution and the location of maximum and average surface temperature of a lithium-ion pouch cell under variable load profiles
Goutam, Shovon; Timmermans, Jean-Marc; Omar, Noshin; Van Den Bossche, Peter; Van Mierlo, Joeri; Rodriguez, Lide Mercedes; Nerea, Nieto; Swierczynski, Maciej

Published in:
European Electric Vehicle Congress

Publication date:
2014

License:
Unspecified

Document Version:
Final published version

Citation for published version (APA):
Surface temperature evolution and the location of maximum and average surface temperature of a lithium-ion pouch cell under variable load profiles.

Shovon Goutam¹, Jean-Marc Timmermans¹, Noshin Omar¹, Peter Van den Bossche¹, Joeri Van Mierlo¹, Lide Rodriguez², Nerea Nieto², Maciej Swierczynski³

¹Mobility, Logistic and Automotive Research Center (MOBI), Department of Electrical Engineering and Energy Technology (ETEC), Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium, Email: Shovon.goutam@vub.ac.be
²IK4-IKERLAN, Miñano Menor, Spain
³Department of Energy Technology, Aalborg University, Aalborg, Denmark

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 sur-
face 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 po-
tential method to observe and measure this spa-
tially non-uniform temperature distribution with
high accuracy.

Despite the high importance of cell surface temper-
ature 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 mi-
cro 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 sur-
face 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, 1 I, 2 I, (20A), and complete discharge
at 0.5 I, 1 I, 2 I, (20A), 2 I, (40A), 3 I, (60A), 4
I, (80A) and 5 I, (100A). The other type included
micro-pulse test at high current rates of 3 and 4 I,
The charge and discharge limits were set with re-
spect 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 be-
 tween. A thermal IR camera (Fluke Ti25) were
used to observe the spatial distribution of cell sur-
face temperature. Additionally, four K type contact
thermocouples (accuracy ± 2° C) were also used to
record the cell surface temperature at specific lo-
cations. 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 envi-
ronment (to avoid visible light interference). More-
over, cell surface was painted uniformly with a dull
black paint.

![Relative positions of thermocouples (TC1-TC4) on the cell surface.](image)

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, and
discharge at 0.5 I, 1 I, 2 I, 3 I, 4 I, and 5 I.

3 Results and Discussion

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

---

1 According to the IEC 61434 standard,
I= C/1h, where C is the discharge capacity of the cell in Ah.
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, 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 discharge. At higher current of 2 I, and 3 I, this effect became trivial, shown by a slight change in the steepness (slop) of the temperature profile. At 4 I and 5 I rate the effect is negligible.

The IR images during discharge (Figure 3) at 5 I 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 3: IR images during discharge at 5 I (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.

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

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
cell. Similar patterns were observed with charge and discharge at other \( I \) 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 \(^\circ\text{C}\)).

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 \(^\circ\text{C}\) 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 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.](image_url)

![Figure 6: Temperature rise during micro-cycle pulse at 3 \( I_t \) and at different SoC levels.](image_url)
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.

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

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

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.

Acknowledgments

This research work was funded by the European Union through the NMP.2013-1 Batteries2020 project (Grant agreement GC.NMP.2013-1 / GA nº 608936). We also acknowledge the support to our research team from the “SoC maakindustrie”.

EEVC European Electric Vehicle Congress
References


Authors

Shovon Goutam graduated as a Mechanical Engineer in 2009 and later obtained his MSc in material engineering in 2013. Presently he is a PhD student working in MOBI, ETEC of Vrije Universiteit Brussel. His research activities involve Characterization, Material development and Modelling of Rechargeable Energy Storage System (RESS) for Electric Vehicles.

dr. ir. Jean-Marc Timmermans
Vrije Universiteit Brussel
Email: jptimmer@vub.ac.be
Jean-Marc Timmermans graduated in 2003 as an Electromechanical Engineer at the Vrije Universiteit Brussel. As an academic assistant of the department of Electrical Engineering and Energy Technology (ETEC), he was involved in several projects related to clean vehicle technologies. In 2010 he obtained a PhD at the Vrije Universiteit Brussel. Currently he is a post-doctoral researcher in the field of electrical energy storage systems and project manager in the Battery Innovation center of the MOBI research group at the Vrije Universiteit Brussel.

Prof. Dr. Eng. Omar Noshin
Vrije Universiteit Brussel
Email: noshomar@vub.ac.be
Noshin Omar was born in Kurdistan, in 1982. He obtained the M.S. degree in Electronics and Mechanics from Erasmus University College Brussels. He is currently the head of Battery Innovation Center of MOBI research group at Vrije Universiteit Brussel, Belgium. His research interests include applications of electrical double-layer capacitors and batteries in BEV’s, HEV’s and PHEV’s. He is also active in several international standardization committees such as IEC TC21/22. He is the author of more than 70 scientific publications.
Prof. dr. ir. Peter Van den Bossche
Email: pvdbos@vub.ac.be
Peter Van den Bossche graduated as civil mechanical - electrotechnical engineer from the Vrije Universiteit Brussel and defended his PhD at the same institution with the thesis "The Electric Vehicle: raising the standards". He is currently lecturer at the engineering faculties of the Vrije Universiteit Brussel, and in charge of coordinating research and demonstration projects for electric vehicles in collaboration with the international associations CITELEC and AVERE. His main research interest is electric vehicle standardization, in which quality he is involved in international standards committees such as IEC TC69, of which he is Secretary, and ISO TC22 SC21.

Prof. dr. ir. Joeri Van Mierlo
Email: joeri.van.mierlo@vub.ac.be
Prof. Dr. ir. Joeri Van Mierlo is a full-time professor at the Vrije Universiteit Brussel, where he leads the MOBI – Mobility, Logistics and automotive technology research centre. A multidisciplinary and growing team of 60 staff members. He is expert in the field of Electric and Hybrid vehicles (batteries, power converters, energy management simulations) as well as to the environmental and economical comparison of vehicles with different drive trains and fuels (LCA, TCO).

Lide Rodriguez is a Senior Researcher of Ikerlan, working in Energy Storage and Energy Conversion devices since 2001. She received her PhD from Cambridge University in 1999. Main research interests are materials science applied into novel concepts for energy storage and conversion. She is also highly interested in PhD supervisions and project managing.

Nerea Nieto graduated in 2009 as chemical engineer from the University of the Basque Country and received the master’s degree in “Research in Applied Engineering” from the University of Navarra, Tecnun. She is currently a PhD student at the Energy Unit of IK4-IKERLAN. Her research interests include thermal modeling of lithium-ion batteries.

Maciej Swierczynski received his B.Tech. degree from AGH University of Science and Technology, Poland in 2005 and M. Tech degree from AGH University of Science and Technology, Poland, Cracow in 2007 in Computer Engineering for Industrial Applications and from Aalborg University, Denmark in 2009 in Power Electronics and Drives. In 2012, he received the Ph.D. degree from Aalborg University, Denmark. He is currently working as a postdoctoral researcher at Aalborg University. His area of research is in energy storage technologies for renewable applications, battery testing, modelling and lifetime analyses.