Development of 2D Thermal Battery Model for Lithium-ion Pouch Cells

Ahmadou Samba[1,2*], Noshin Omar[2], Hamid Gualous[1], Peter Van den Bossche[2], Joeri Van Mierlo[2], Tala Ighil Boubekeur[1]

[1] *Université de Caen Basse Normandie, Rue Louis Aragon, 50130 Cherbourg-Octeville, France*

[2] *Vrije Universiteit Brussel, Pleinlaan 2, 1050, Brussels, Belgium*

*ahmadou.samba@vub.ac.be

Abstract

This paper represents a simulation model for a 2D-thermal model applied on a Lithium-ion pouch battery. This model is able to describe the transient response of the thermal distribution accurately. The heat generation parameters used in this model have been obtained experimentally from dedicated estimation technique. The experimental and simulation are performed at different charge and discharge current rates. The experimental results are in good agreement with the developed model. The battery thermal distributions using natural and forced convection cooling are studied.

Keywords: Lithium-ion battery; Pouch cell; Entropy; Resistance; Temperature distribution; ANSYS®; Thermal imager

1 Introduction

As the global economy begins to strain under the pressure of rising petroleum prices and environmental concerns, research have spurred into the development of various types of clean energy transportation systems such as Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs) and Plug-In Hybrid Electric Vehicles (PHEVs) [1-5].

Lithium-ion batteries play an important role as energy carriers in our society mainly in BEVs and HEVs. During discharging or charging, various exothermic chemical and electrochemical reactions occur. These phenomena generate heat that accumulate inside the battery and therefore accelerate the reaction between cells components. With higher discharge/charge current rates, the heat generation in a battery increases significantly. If heat transfer from the battery to the surroundings is not sufficient, the battery temperature can rise very fast and in the worst-case scenario thermal runaway can occur [1, 6].

In order to meet the safety issues on one hand and to increase its performance on other hand, the knowledge of the battery temperature distribution is necessary. Therefore a good use of batteries may increase its lifetime and performance. In this work, a lithium iron phosphate pouch cell with a rated capacity of 45Ah has been used. In order to keep the cell temperature in the safe temperature range, there is a need of a thermal model to predict the cell temperature distribution over the surface of the battery and maintain an equal heat distribution.

Due to the large size and small thickness of the lithium-ion pouch cell used in this work, a 2D thermal model is developed to predict the transient response of the surface thermal distribution by

using the ANSYS$^®$ software at different charge/discharge current rates. Because of the high dependency of the internal resistance as function of SoC, current rate and working temperature, the proposed thermal model has been associated with the 1D electrical battery model.

2   Thermal Modeling

Taking into account the small thickness of the used lithium-ion pouch battery the heat distribution in the y-direction has been neglected. Therefore a two-dimensional transient model has been developed. As shown in Figure 1, the size and different domains (Tabs, case and electrodes domains) of the battery are described. These domains are made of different materials. A transient heat conduction equation is sufficient to describe the thermal phenomena in the battery and the convective term inside the battery (electrode-electrolyte) can generally be neglected [12].
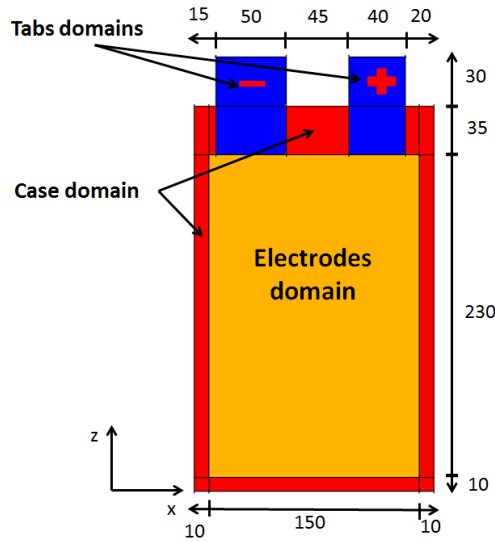

Figure 1: Schematic diagram and dimension (mm) of Li-ion pouch battery

Based on the above assumptions, the energy balance equation over a representative elementary volume (REV) in a battery, enable to predict the transient response of the temperature distribution for the 2D thermal modeling is formulated as:

- In Electrodes domain

$$k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right] + q_g = \rho . C_p \frac{\partial T}{\partial t} \qquad (1)$$

$$q_g = \frac{1}{V_{bat}}\left[RI^2 + \left(T\left[\frac{dE}{dT}\right]\right)I\right] \qquad (2)$$

- In case and tabs domains

$$k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right] = \rho . C_p \frac{\partial T}{\partial t} \qquad (3)$$

Where ρ (kg.m^{-3}), C_p (J.kg^{-1}.K^{-1}), and k (W.m^{-1} K^{-1}) are the average density, the average specific heat and the average thermal conductivity along the x-direction and z-direction, respectively.

The density heat flux from battery surface to the surrounding is given by both the radiation and the convection heat contributions:

$$q_s = h(T - T_a) + \epsilon\sigma(T^4 - T_a^4) \qquad (4)$$

Where h (W.m^{-2}.K^{-1}) represents the convective heat transfer, ε the emissivity of the cell surface, σ the Stefan–Boltzmann constant, T the battery surface temperature and Ta the ambient temperature. Because of the use of a thermal camera, the battery is painted black, and then the emissivity is taken equal to 1. In this case the cell is cooling by natural convection.

In natural convection, the Rayleigh number controls the flow regime [21]. The Rayleigh number is defined as:

$$Ra = \frac{g\beta_{air}(T - T_a)L^3}{v_{air}^2} \qquad (5)$$

Where:
β_{air} : The coefficient of thermal expansion (1/°C)
v_{air} : The cinematic viscosity (m^2/s)
g: The acceleration of gravity (m/s^2)
L: The length of the battery (m)

In laminar convection, where

$$10^3 < Ra < 10^9 \qquad (6)$$

$$h = 0.59\frac{\lambda_{air}}{L} Ra^{0.25} \qquad (7)$$

In turbulent convection, where

$$10^9 < Ra < 10^{14} \qquad (8)$$

$$h = 0.10\frac{\lambda_{air}}{L} Ra^{0.33} \qquad (9)$$

λ_{air}: The thermal conductivity of air $(W.m^{-1}.K^{-1})$

The thermal parameters used in this work are listed in Table 1.

ρ (kg. m^{-3})	C_p (J.kg^{-1} .K^{-1})	k (W.m^{-1}.K^{-1})	h (Wm^{-2} K^{-1})	σ (Wm^{-2} K^{-4})
2247	785	30	3	5.669 10^{-8}

Table 1 : Parameters used for thermal modelling

Furthermore, q_g (W.m^{-3}) is the volumetric heat source, where R (Ω) is the internal resistance, $\frac{dE}{dT}$ (V.K^{-1}) the entropy coefficient and I (A) the current (negative during discharge and positive during charge).

Knowing the heat generation change and thermal parameters, finite volume numerical method is used to solve the energy balances by ANSYS software. The thermal model is validated by comparing with the experimental measurements.

A test bench has been set-up to charge the battery until the maximum voltage (V$_{max}$: 3.65 V) and also to discharge it until the cut-off voltage (V$_{min}$: 2V) with different It-rate (0.33 It, 2/3 It and 1 It). In order to analyze the thermal distribution of the battery, several thermocouples are placed on the battery surface and the ambient air as shown in Figure 2 and a thermal camera is also used.
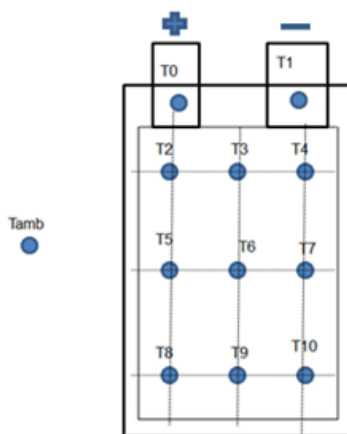

Figure 2: Thermocouples position on the battery

3   Results

The electrical characterization of the used cell, based on Omar et al work [10], is performed by identifying from the HPPC tests (10s pulse) the internal resistance of the electrical model at different current, temperature and also SoC.

Figure 3 and Figure 4 show the internal resistance variation in function of SoC and temperature at 1 It charge and discharge process. As we can observe the internal resistance of the battery increases the more the working temperature and the SoC decrease. For the investigated lithium-ion battery the internal resistance varies between 8mΩ and 2mΩ. The internal resistance is also measured at different currents. The internal resistance is also high at very high SoC.

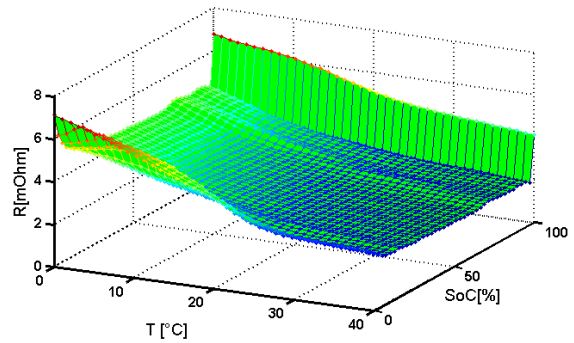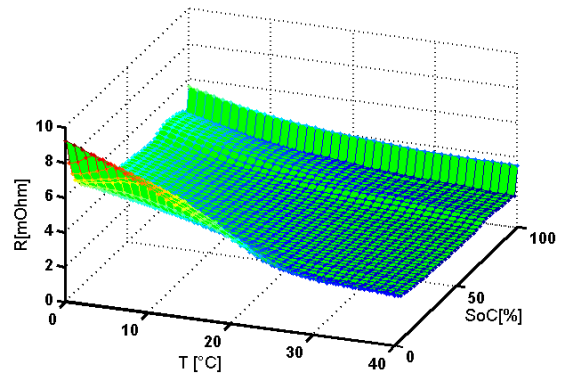Figure 3: Internal resistance of charge in function SoC and temperature at 1 It =45A

Figure 4 : Internal resistance of discharge in function SoC and Temperature at 1 It =45A

The entropy coefficient for a given SoC is obtained experimentally from the slope of the curve of the open circuit voltage (OCV) as a function of temperature. Then the experiment has been, repeated at every SoC level. Figure 5 shows the measurements of the entropy coefficient in function of SoC during charge and discharge process. For low charge or discharge rate, the

reversible heat becomes dominant than the irreversible heat. According to the reversible heat formula ($\left(T\left[\frac{dE}{dT}\right]\right)I$), this term may be positive or negative depending the sign of the current (positive in charge and negative in discharge) and also the sign of the entropy coefficient. If the reversible heat is positive then the chemical reactions are exothermic otherwise they are endothermic. Physically, an endothermic reaction is obtained when the chemical bonds of the reactants are higher than those of the products: then extra energy should be absorbed from the external environment to create new bonds. During exothermic reaction the opposite situation occurs.
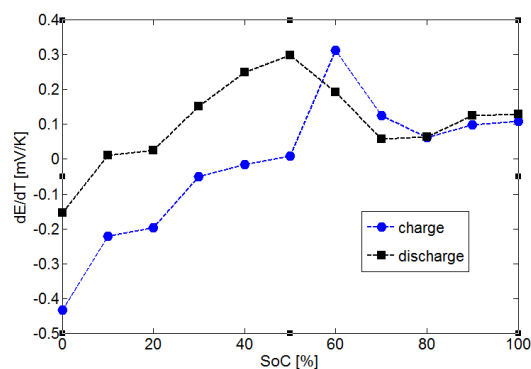

Figure 5: Entropy coefficient as a function of state of charge (SoC)

Figure 6 shows the comparison of the full thermal distributions of the cell between the thermal imager measurement and the model results at different time steps at 1 It charge capacity test, where the battery has been charged at 1I t until the maximum voltage (3.65V) has been reached. This indicates that the battery surface temperature is nearly uniform, excepted in the middle where the maximum temperature is located by the thermocouple T6. The maximum temperature difference on the surface of the battery is about 0.7°C.

As we observe in Figure 7, the simulation results at different It-rates are in good agreement with the experimental results. The error varies between 0 – 0.7°C. The full thermal distribution of the cell has also been investigated at 1 It discharge capacity test, where the thermal imager measurements are compared to the model as shown in Figure 9.

This comparison shows a thermal distribution slightly uniform except at the end of discharge, where the maximum temperature difference is equal to 3.4°C. The hottest zone is also located at the centre of the battery as in charge process. The model is also validated by the thermal imager measurements at discharge capacity test
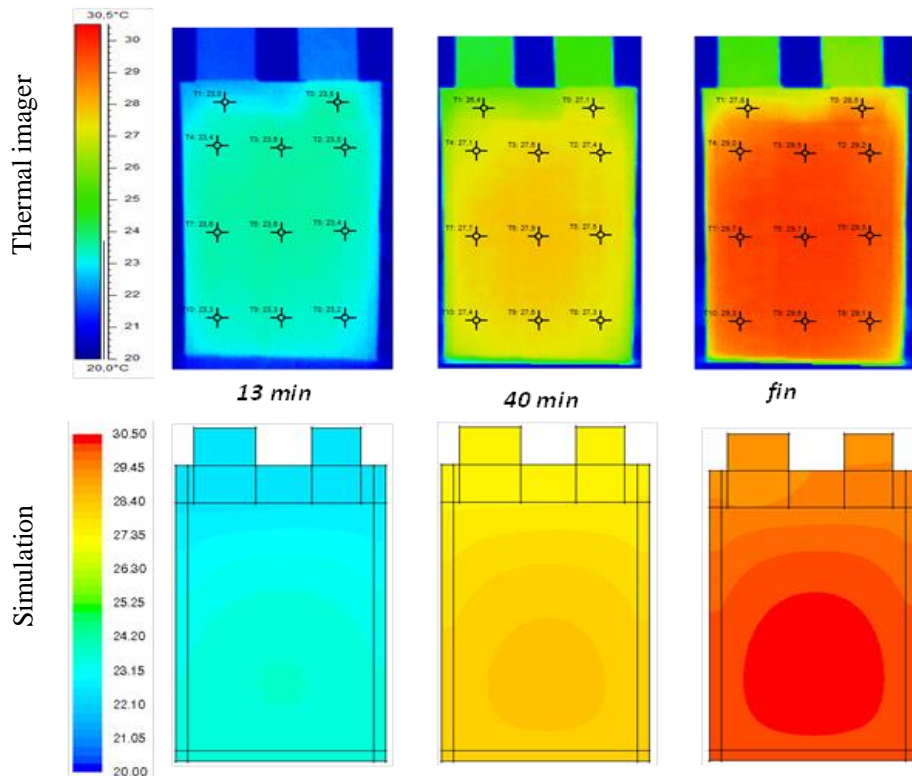
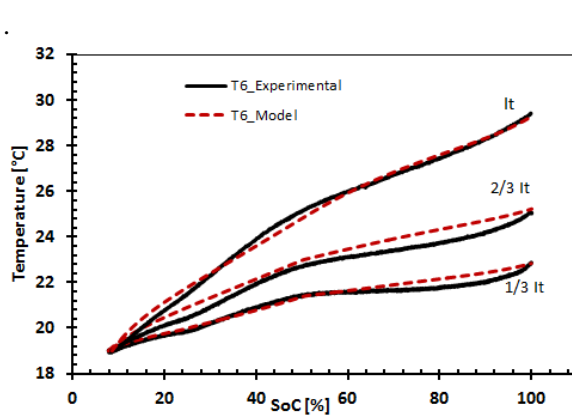Figure 6: Thermal distributions based on experimental thermal imager and modelling at 1 It charge rate

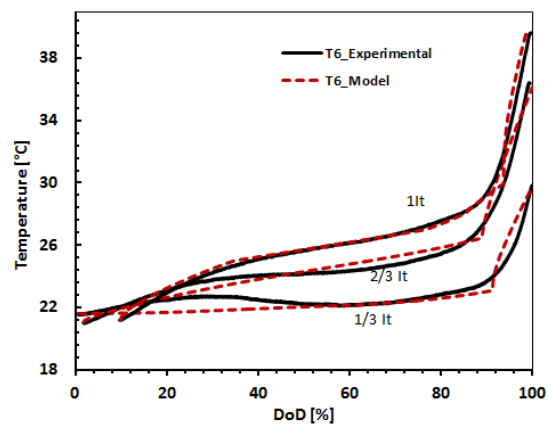Figure 7: Comparison between experimental and model results at different charge rates

Figure 8 : Comparison between experimental and model results at different charge rates

The same test has been performed at different discharge It-rates and compared to the model as shown in Figure 8. The simulation results are in good agreement with the experimental results, where the error varies between 0-1.5°C

In EVs and HEVs applications, the batteries are usually subjected to heavy demands such as fast charge and quick acceleration of the vehicles. These solicitations increase significantly the battery temperature and may exceed the safety range temperature. Thus, to avoid this, there is a need for a good cooling system. The appropriate cooling system depends on the applied heat transfer coefficient
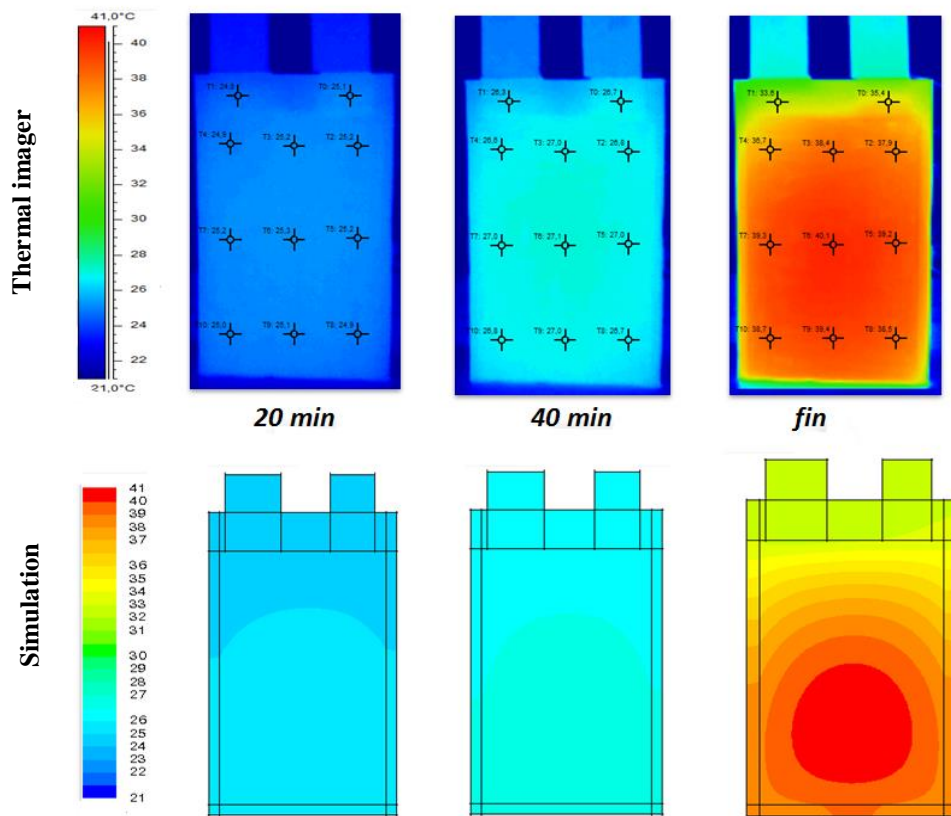
Figure 9 : Thermal distributions based on experimental thermal imager and modelling at 1 It discharge current rate

. In order to evaluate this aspect, the model is used to simulate at 1 It of charge, with an ambient temperature about 20 °C and at different heat transfer coefficient. In Figure 10, the influence of the heat transfer coefficient is investigated and shows that more the heat transfer coefficient is important, the more is the heat transfer from battery to the surrounding and then less is the temperature.

At natural convection, where h varies from 3 till 10 W/m^{2}K, the maximum temperature increase is about 10°C. At forced convection, where h varies from 10 to 100 W/m^{2}K the maximum temperature increase is about 5°C.

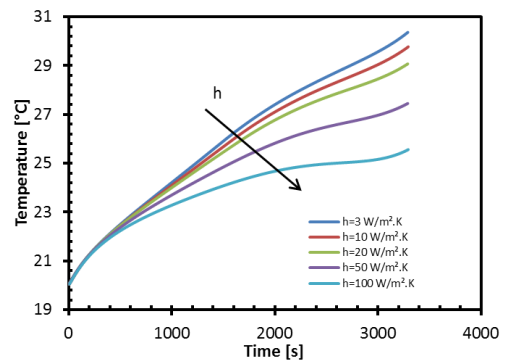Figure 10 : Evolution of the surface temperature at different heat transfer coefficient at 1 It, which current rate?

Conclusion

In this work, a 2D thermal model is developed for a large size lithium iron phosphate pouch battery cell, which is able to predict the surface temperature distribution of the battery at different current rate and ambient temperature. The experimental results show a thermal distribution

slightly uniform, with 0.7°C of maximal temperature difference, during charge and discharge process excepted at the end of discharge where the maximal temperature difference is equal to 3.4°C. The simulation results performed at different current rates are in good agreement with the experimental results, where the error varies between 0-1°C and also identify the localization of the hottest zone at the centre of the battery.

Finally more the heat transfer coefficient is important, the more is the heat transfer from battery to the surrounding and less is the battery surface temperature.

References

[1] IEA (International Energy Agency) (2008), Energy Technology Perspectives – Scenarios and strategies to 2050. OECD Publishing, Paris, France.

[2] Van Mierlo, J.; Maggetto, G. Comparison of the environmental damage caused by vehicles with different alternative fuels and drive trains in a Brussels context. J. Automobile Engineering 2003, 36, 583-593.

[3] Boureima F.S. Environmental Assessment of Conventional and Alternative Vehicles and Fuels in a Belgian Context, PhD Thesis, Vrije Universiteit Brussel, Brussels, Belgium, September 2011.

[4] Axsen, J.; Kurani, K.S.; Burke, A. Are batteries ready for plug-in hybrid buyers? J. Transport Policy 2010, 17, 173-182.

[5] Van den Bossche, P.; Vergels, F.; Van Mierlo, J.; Matheys, J.; Van Autenboer, W.; SUBAT: an assessment of sustainable battery technology. J. Power Sources 2006, 162, 913-919.

[6] Omar, N.; Daowd, M.; Mulder, G.; Timmermans, J.M.; Van Mierlo, J.; Pauwels, S. Assessment of Performance of Lithium ion Phosphate Oxide, Nickel Manganese Cobalt Oxide and Nickel Cobalt Aluminum Oxide Based Cells for Using in Plug-in Battery Electric Vehicle Applications. International Conference Vehicle Power and Propulsion Conference. September 6-9, 2011, Chicago, USA.

[7] Omar, N.; Verbrugge, B.; Mulder, G.; Van den Bossche, P.; Van Mierlo, J.; Daowd, M.; Dhaens, M.; Pauwels, S. Evaluation of performance characteristics of various lithium-ion batteries for use in BEV application. International Conference Vehicle Power and Propulsion Conference. September 1-3, 2010, Lille, France.

[8] Omar, N.; Daowd, M.; Verbrugge, B.; Mulder, G.; Van den Bossche, P.; Van Mierlo, J.; Dhaens, M.; Pauwels, S.; Leemans, F. Assessment of Performance Characteristics of Lithium-Ion Batteries for PHEV Vehicles Applications Based on a Newly Test Methodology, The 25th International Conference on Battery, Hybrid and Fuel Cell Electric Vehicle. November 5-8, 2010, Shenzhen, China.

[9] Burke, A.; Miller, M. Performance Characteristics of Lithium-ion Batteries of Various Chemistries for Plug-in Hybrid Vehicles, The 24th International Conference on Battery, Hybrid and Fuel Cell Electric Vehicle. May 13-16, 2009, Stavanger, Norway.

[10] Omar, N.; Van den Bossche, P.; Daowd, M.; Hegazy, O.; Smekens, J.; Coosemans, Th.; Van Mierlo, J. Rechargeable Energy Storage Systems for Plug-In Hybrid Electric Vehicles -Assessment of Electrical Characteristics. J. Energies 2012, 5, 2952-2988.

[11] Kim Gi-heon, Pesaran Ahmad, Battery Thermal Management Design Modeling, The World Electric Vehicle Association Journal, Vol. 1, 2007

[12] Kim Gi-Heon, Pesaran Ahmad, Spotnitz Robert, A three-dimensional thermal abuse model for lithium-ion cells, Journal of Power Sources 170 (2007) 476–489

[13] J. P. Schmidt, D. Manka, Dino Klotz, E. Ivers-Tiffée, Investigation of the thermal properties of a Li-ion pouch-cell by electrothermal impedance spectroscopy, Journal of Power Sources 196 (2011) 8140–8146

[14] Monzer Al Sakka, Hamid Gualous, Joeri Van Mierlo, Hasan Culcu, Thermal modeling and heat management of supercapacitor modules for vehicle applications, Journal of Power Sources 194 (2009) 581–587

[15] Thomas Karen E., Newman John, Heats of mixing and of entropy in porous insertion Electrodes, Journal of Power Sources 119–121 (2003) 844–849

[16] S. Al Hallaj, H. Maleki, J. S. Hong, J. R. Selman, Thermal modeling and design considerations of lithium-ion batteries, Journal of Power Sources 83 1999 1–8

[17] C. Forgez, D. Vinh Do, G. Friedrich, M. Morcrette, C. Delacourt, Thermal modeling

of a cylindrical LiFePO4/graphite lithium-ion battery, Journal of Power Sources 195 (2010) 2961–2968

[18] Y. Inui, Y. Kobayashi, Y. Watanabe, Y. Watase, Y. Kitamura, Simulation of temperature distribution in cylindrical and prismatic lithium ion secondary batteries, Energy Conversion and Management 48 (2007) 2103–2109

[19] Matteo Muratori, thermal characterization of lithium-ion battery cell, phd Report, 2008-2009

[20] D. Bernardi, et al., A general energy balance for battery systems, Journal of the Electrochemical Society, vol. 132, pp. 5-12, 1985.

[21] J.P. Holman, Heat Transfer, ninth ed., Mc Graw Hill, 2002

Authors

Eng. Ahmadou Samba
University of Can Basse Normandie
Vrije Universiteit Brussel

Email: ahmadou.samba@vub.ac.be
Ahmadou Samba was born in Senegal. He obtained the M.S. degree in Energy and Mechanics from Ecole des Mines of Nancy in France. He is currently pursuing a joint PhD degree in the department of Electrical Engineering and Energy Technology ETEC at the Vrije Universiteit Brussel and also in the department of Energetic system at the University of Caen Basse Normandie, France. His research interests include applications of supercapacitors and batteries in term of electrical characterization and thermal management.

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 and PhD degree in the department of Electrical Engineering and Energy Technology ETEC, at the Vrije Universitit Brussel, Belgium. He is currently team leader of the Rechargeable Energy Storage System

group of the Vrije Universiteit Brussel. His research interests include applications of BEV's/HEV's/PHEV's, electrical modeling, thermal modeling, lifetime modeling of electrical-double layer capacitors, batteries and hybrid capacitors. He is also active in several international standardization committees such as IEC TC21/22.

Prof. Dr. Ir. Hamid Gualous
University of Can Basse Normandie

Email: hamid.gualous@unicaen.fr
Hamid Gualous received his Ph.D. degree in electronic from the University Paris XI Orsay, France, in 1994. From 1996 to 2009 he was an Associate Professor at the University of Franche-Comte, FEMTO-ST Laboratory , France. Since 2009, he is Full Professor at the University of Caen Basse Normandie, France. His main research activities are concerning energy storagedevices (supercapacitors and batteries), hybrid power sources (fuel cell-supercapacitor battery) and energy management for vehicle applications.

Prof. Dr. Ir. Van den Bossche Peter
Vrije Universiteit Brussel
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 faculty of the Vrije Universiteit Brussel, and in charge of co-ordinating 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.

ageing.

Prof. Dr. ir. Joeri Van Mierlo
Vrije Universiteit Brussel
Email: jvmierlo@vub.ac.be
Joeri Van Mierlo obtained his Ph.D. in electromechanical Engineering Sciences from the Vrije Universiteit Brussel in 2000. He is now a full-time professor at this university, where he leads the MOBI – Mobility and automotive technology research centre (http://mobi.vub.ac.be). Currently his activities are devoted to the development of hybrid propulsion (power converters, energy storage, energy management, etc.) systems as well as to the environmental comparison of vehicles with different kind of drive trains and fuels (LCA, WTW). He is the author of more than 200 scientific publications. Prof. Van Mierlo chairs the EPE chapter "Hybrid and electric vehicles" (www.epe-association.org); he is the secretary of the board of the Belgian section of AVERE (ASBE) (www.asbe.be) and is Vice-president of AVERE (www.avere.org). He is editor in chief of the World Electric Vehicle Journal Volume 3 and co-editor of the Journal of Asian Electric Vehicles. He is an active member of EARPA – the European Automotive Research Partner Association. Furthermore he is member of Flanders Drive and of VSWB – Flemish Cooperative on hydrogen and Fuels Cells. Prof. Van Mierlo was Chairman of the International Program Committee of the International Electric, hybrid and fuel cell symposium (EVS24).
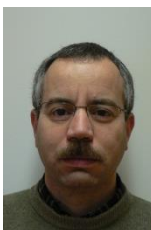
Dr. Ir. Tala-ighil Boubekeur
University of Can Basse Normandie
boubekeur.tala- ighil@unicaen.fr

Tala-ighil Boubekeur received his joint Ph.D. degree in electronic from the University of Montpellier II, France and the University of Bejaïa, Algeria. He is currently an Associate Professor of electrical engineering and power electronics at the University of Caen Basse Normandie, France. His main research activities are concerning energy storagedevices (supercapacitors and batteries), and power devices