ELECTRO-THERMAL SIMULATION OF LITHIUM ION BATTERIES FOR ELECTRIC AND HYBRID VEHICLES

Zul Hilmi CHE DAUD[(a)], Daniela CHRENKO[(b)], Fabien DOS SANTOS[(c)], El-Hassane AGLZIM[(d)] , Luis LE MOYNE[(e)]

[(a)]IEEE Student Member. Mechanical Engineering Faculty,
University of Technology Malaysia, 81310 Skudai, Johore, Malaysia.
[(b)]IEEE Member.
[(a), (b), (c), (d), (e)]DRIVE Laboratory, Institut Supérieur de l'Automobile et des Transports (ISAT),
University of Burgundy, 49 rue Mlle Bourgeois, 58027 Nevers, France.

[(a)]hilmi@fkm.utm.my, [(b)]daniela.chrenko@u-bourgogne.fr, [(c)]fabien.dos-santos@u-bourgogne.fr,
[(d)]el-hassane.aglzim@u-bourgogne.fr, [(e)]luis.le-moyne@u-bourgogne.fr

ABSTRACT

A lithium ion battery is analyzed with regard to its thermal behaviour using modelling. Therefore resistive energy losses are translated into generated heat inside the battery, which is evacuated by forced convection, thus forming an electro-thermal model. Based on that model, simulations are done using OpenFOAM. The simulation underlines the observation that batteries have higher temperature close to the connectors and that temperature increase depends highly on discharge rate.

Keywords: electric and hybrid vehicle, lithium ion battery, thermal electric modelling

1. INTRODUCTION

In electric and hybrid vehicles, batteries are among the most important key components which must continually accept and provide electrical energy by transforming chemical energy into electrical energy and vice versa (Ehsani et al. 2005, Larminie and Lowry 2003). Batteries are desired to have high specific power, high specific energy, long calendar and cycle life, low initial and replacement cost, high reliability and high robustness.

Most commonly used batteries are lead-acid, nickel-cadmium, nickel-metal hydride and lithium-ion battery (Guzzella and Sciarretta 2007). Since the beginning of automotive engineering the lead acid battery is the most used type of battery. It is still used in almost every car for the 12V electric power supply. Due to its limited specific energy it has been replaced by Nickel-Metal Hydride batteries for hybrid application for example in the Toyota Prius (Toyota motor sales 2013).

Finally Lithium based batteries propose higher specific energy, but they have to be supervised and controlled carefully, in order to assure their operation (Shafiei et al. 2011, Väyrynen and Salminen 2012). Figure 1 shows the volumetric energy density against gravimetric energy density for common batteries (Amjad et al. 2010, Väyrynen and Salminen 2012), and figure 2 shows the Ragone plot of specific power density versus specific energy density of various electrochemical energy storage and conversion devices (Pollet et al. 2012).

Lithium-ion batteries are therefore likely a good choice for electric and hybrid vehicles due their superior properties such as high power rating, high energy density, and high cycle life (Ehsani et al. 2005, Chacko and Chung 2012, Larminie and Lowry 2003, Sen and Kar 2009, Urbain et al. 2007) and they are considered as the most promising technology in the next decades (Gerssen-Gondelach and Faaij 2012).

The temperature is one of the parameters of a lithium ion battery that has to be controlled carefully, as the optimum working region is normally limited between 20°C and 65°C (Abdul-Quadir et al. 2011, Al-Hallaj and Selman 2002, Baronti et al. 2010). Furthermore, the working temperature of the lithium ion battery has a big influence on its internal resistance, hence efficiency, cell degradation, and hence life time.

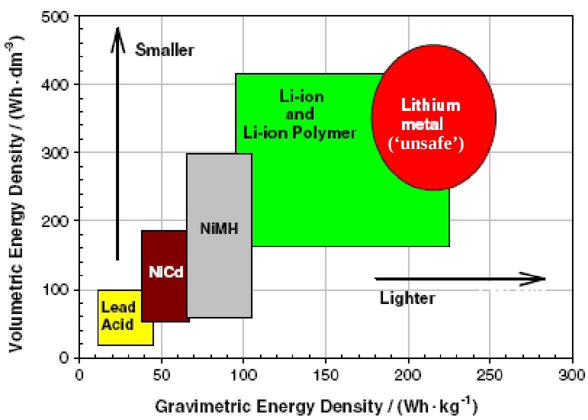


Figure 1: Plot of Volumetric Energy Density against Gravimetric Energy Density for Common Batteries (Amjad et al. 2010, Vayrynen and Salminen 2012)

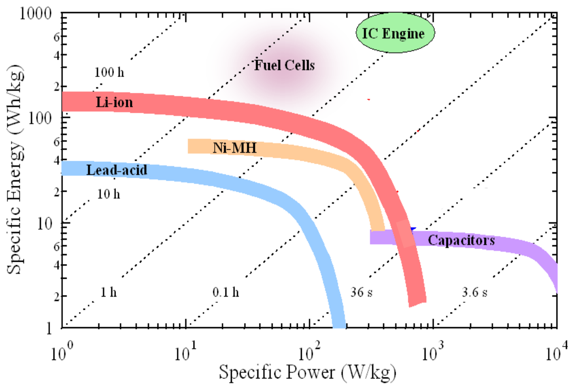


Figure 2: Ragone Plot of Specific Power Density vs. Specific Energy Density of Various Electrochemical Energy Storage and Conversion Devices (Pollet et al. 2012)

This is why an electro-thermal model is presented. First the physical behaviour of a lithium ion battery is described, followed by and introductions to its electro-thermal modelling as well as the modelling software OpenFOAM, which provides the possibility to integrate electric behaviour, like heat generation due to electric resistance into a CFD model. Results for different working conditions are presented in section 3. The article closes with conclusions and perspectives.

2. THERMO ELECTRIC DESCRIPTION

2.1. Thermo Electrical Description of Battery

There are basically four main methods in battery modelling (Bhide and Shim 2011, Tan et al. 2011): mathematical models, electrochemical models, polynomial-based models and electrical models.

Mathematical models are the easiest but the least accurate model (Tsang et al. 2010). It cannot provide any I-V information and most of them only work for specific applications (Bhide and Shim 2011). Electrochemical models, based on chemical reactions occurring inside the battery cells (Shafie et al. 2011), are complex and time consuming but able to produced more accurate result. Polynomial-based models use a simplistic expression containing state of charge (SOC) to represent a battery. These models have limited capacity in presenting the I-V information (Bhide and Shim 2011).

Electrical models are based on a combination of voltage sources and other electrical components such as resistors, and capacitors that describe the electrochemical processes and dynamics of a battery (Shafie et al. 2011, Tsang et al. 2010). Electrical models are more realistic, intuitive, and easy to handle as compared to other models. Furthermore, it can be applied to any battery model irrespective of its chemistry, configuration and rate of discharge; by using suitable combination of parameters (Tan et al. 2011).

Most of the existing electrical models can be grouped into three main basic categories, which is Thevanin-based models, impedance-base models, and runtime-based models (Chen and Rincon-Mora 2006). Thevanin-based models use series resistor and RC parallel network(s) to predict the battery response to transient load events. Impedance-based models use electrochemical impedance spectroscopy method to obtain an equivalent impedance model in the frequency domain, and then use a complicated equivalent network to fit the impedance spectra. On the other hand, runtime-based models use a complex circuit network to represent the battery runtime and voltage response for a constant discharge current (Chen and Rincon-Mora 2006). Figure 3 shows a simple electrical equivalent circuit model for a single lithium-ion battery cell as proposed by Thirugnanam et al. (Thirugnanam et al. 2012). This model consists of series resistor R_s, and an RC parallel network composed of R_1 and C_1.

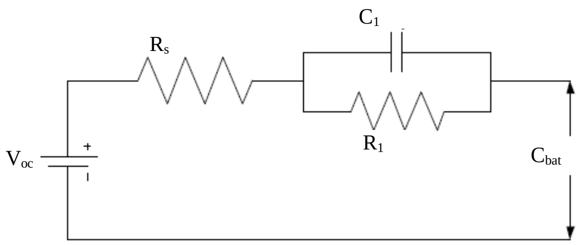


Figure 3: Single Cell Electrical Equivalent Circuit Model (Thirugnanam et al. 2012)

Temperature is an important factor that affects the battery pack performance and life time (Shafie et al. 2011). It is proved experimentally that for the increase of each 10°C in the operating temperature compared to the nominal temperature of the designed battery pack, the life cycle of the batteries will reduce approximately to half of the nominal life cycle (Shafie et al. 2011). Furthermore, temperature of each battery cell is different throughout the battery pack depending on the battery pack design.

The difference in temperature between the individual cells in a battery pack might be the result of the difference of forced convection at the various points of the battery pack surface, which is caused by the different conditions of air speed and initial air temperature. Another reason is non-uniform impedance distribution among cells, and difference in heat transfer efficiency among cells (Al-Hallaj and Selman 2002). Non-uniform impedance may result from defects in quality control and also difference in local heat transfer rate. While, the differences in heat transfer efficiency depends on where the cell is positioned in the battery pack.

The temperature difference may then lead to further difference in impedance which amplifies the capacity imbalance among the cells that further causes the cells to be over-charged or over-discharged during cycling (Abdul-Quadir et al. 2011, Al-Hallaj and Selman 2002). This is the major contribution to premature failure in the battery packs in form of thermal runaway or accelerating capacity fading (Abdul-Quadir et al. 2011, Al-Hallaj and Selman 2002). The BMS (battery management system) is intended to provide a supervision of the individual cells in order to improve the battery pack performance and decrease risks. The supervision provided by the BMS includes not only the cell voltage, charging and discharging current, but can also include an interface to the cooling system (Martel et al. 2011, Sen and Kar 2009, Shafie et al. 2011).

2.2. Thermal Modelling

Thermal modelling of the battery packs is very important, helping in designing battery management systems for better performance such as to prevent battery degradation and extend battery lifetime (Martel et al. 2011) and also preventing safety risks such as thermal runaway (Shafie et al. 2011). An accurate thermal model of battery packs (Shafie et al. 2011) and the individual cell is very important in order to illustrate the real condition of the battery temperature and prevent any potential abuse (Sen and Kar 2009, Vayrynen and Salminen 2012).

The local heat generation in the battery cell due to the electrochemical reactions and mass transfer of ions in the electrolyte can be characterized by local internal resistance and the current densities (Chacko and Chung 2012). The battery cell temperature is calculated based on internal energy balance that can be described by:

$$m \cdot C_p \cdot \frac{dT(t)}{dt} = R \cdot i^2(t) - (Q_{conv} + Q_{rad}) \quad (1)$$

Where m stands for the cell mass (kg), C_p is the specific heat capacity (J/kg.K), T the cell temperature (K), i the charge/discharge current (A), and R the cell internal resistance (Ω). Q_{conv} represent the convection heat energy, and Q_{rad} the radiation heat energy.

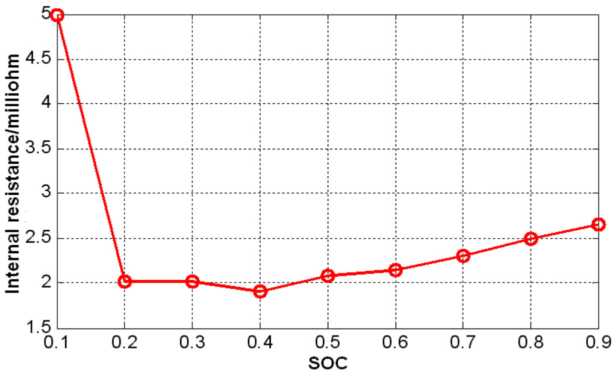


Figure 4: Relationship of Internal Resistance and SOC (Lin et al. 2009)

Generally, the battery internal resistance, R is described as a function of battery state of charge (SOC) (Chen and Rincon-Mora 2006, Kroeze and Krein 2008, Lin et al. 2009). The value of resistance is approximately constant over 20% to 90% SOC as shown in figure 4. The battery internal resistance also varies with temperature. Figure 5 illustrates the effect of temperature on the variation of the battery internal resistance as presented by Sen and Kar (Sen and Kar 2009). It shows that the battery resistance slightly changes with the change of the battery temperature (Sen and Kar 2009).

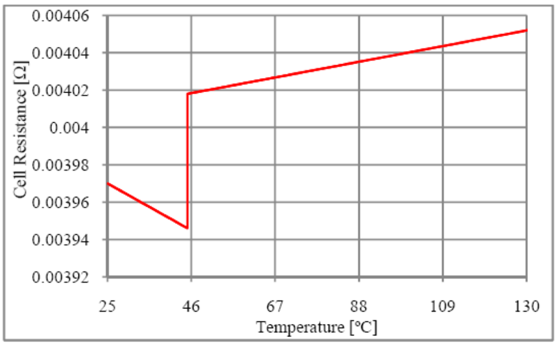


Figure 5: Cell Resistance Variations with Temperature (Sen and Kar 2009)

In this project the value of internal resistance will be first considered as constant for an easier model manipulation. This is justified by the fact that the battery normally will not be fully discharge (not less than 20% SOC) to avoid any potential damage to the battery, where the resistance is approximately constant over 20% to 90% SOC as shown in figure 4. Also, from figure 5 we can conclude that the variation of resistance in the temperature range of 25 ºC to 130 ºC is less than 1.8 % from its initial value at the temperature of 25 ºC. Here, 2 mΩ is used as the battery internal resistance.

The convection heat transfer, Q_{conv} of the battery cell surface can be expressed as in equation 2 (Mousavi et al. 2012, Tan et al. 2011).

$$Q_{conv} = hA(T_s - T_c) \quad (2)$$

Where h represent the convective heat transfer coefficient (W m^{-2} K^{-1}), A the cell surface area (m^2), T_s the cell surface temperature (K) and T_c the cooling air temperature (K). The convective heat transfer coefficient depends on the cooling fluid and the types of fluid flow (Tan et al. 2011). In this work, air is used as the cooling fluid. Here the convection type can be considered as force convection as moving air is introduced to the system. The radiation heat transfer is ignored in this stage of work because it is less significant as compared to force convective heat transfer.

During charge/discharge process, all the current flows to the positive and negative terminal from the entire electrode plate (Kim et al. 2009). Thus, the current densities and consequently the temperature of positive and negative terminal are higher than the other parts of the battery cell (Kim et al. 2009). Furthermore, the temperature at the positive terminal is higher than the negative terminal due to lower electrical conductivity of the positive electrode, despite the fact that the current flow in both terminal are similarly high (Chacko and Chung 2012).

2.3. OpenFOAM

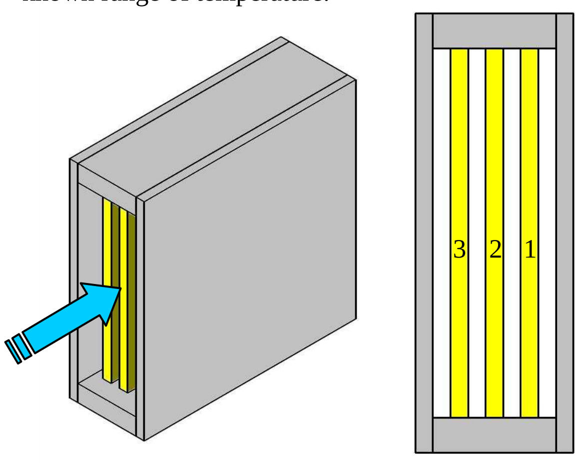
OpenFOAM is a free, open source CFD software package produced by OpenCFD Ltd for numerical simulation written in the C++ programming language (OpenCFD Ltd., 2011). OpenFOAM is gaining popularity in both academic research and industrial users (Jasak et al. 2007). This is because of several factors:

- Free, open source software, meaning that complete source code is available to all users at no cost.
- Flexibility and extensive capability, where users are free to customize and extend its existing functionality.
- Capability to solve complex problems from complex fluid flows, solid dynamic to electromagnetic that can level up with commercial CFD.
- Expressive and versatile syntax, allowing easy implementation of complex physical model.

2.4. Modelling Conditions

In this project, a three cells lithium ion battery pack is modelled using OpenFOAM. The cells are arranged in parallel to each other in a battery box, as shown in figure 6. The blue flesh shows the airflow direction. The battery cells are connected in series electrical connection. The space between each cell is 10 mm to allow the air to circulate and act as forced cooling system that takes the heat from cell surface to the environment.

The battery cells used in this project are Kokam SLPB 100216216H cells and have a typical capacity of 40 Ah and nominal voltage of 3.7 V. Each cell has a weight of 1.1 kg with dimensions of 10 mm thickness, 215 mm width, and 210 mm length as shown in figure 7. Cell properties such as density, thermal conductivity and specific heat capacity are assumed to be uniform throughout the battery and to remain constant within a known range of temperature.



(a) (b)

Figure 6: 3 battery cells arranged in a box with (a) represent the isometric view and (b) the front view

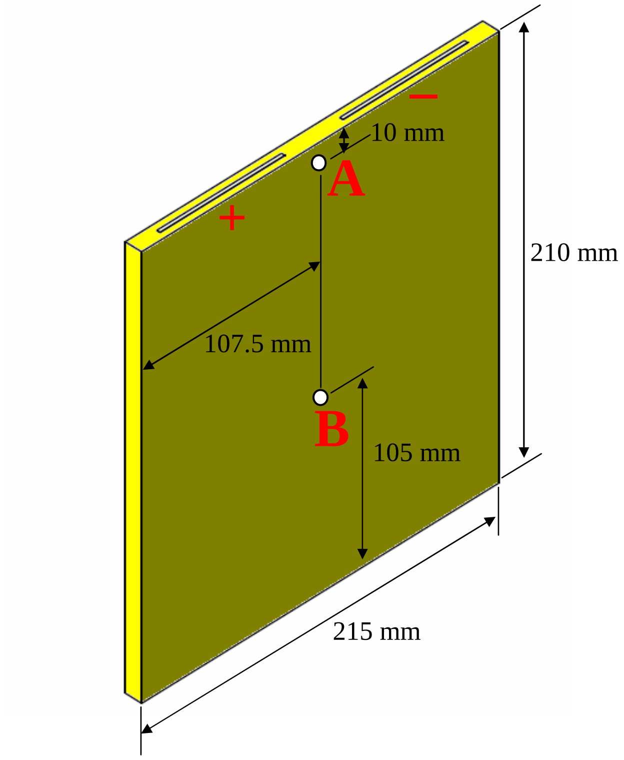


Figure 7: Battery Cell Parameters

3. RESULTS AND DISCUSSION

Figure 8 shows the surface temperature of the 1st battery cell at the end of discharge with 5C discharge rate. Here, a constant air velocity at inlet of 3 m/s and air at ambient temperature is used as a cooling system. We considered that the ambient air temperature is at 25 °C.

It can be seen that the temperature near the battery positive and negative terminal is higher than at the other location on the cell surface. This is due to different current densities at cell terminal and electrode plate as explained in section 2.2. The temperature near the positive terminal is also higher than at the negative terminal. Figure 9 shows the airflow inside the battery box and between the battery cells. The value of air velocity between the battery cells is higher than the initial inlet velocity due to the reduced in volume.

Figure 10 shows the temperature cell surface of the 1st battery cell at two different points A and B (as marked in figure 7) for different discharge rate of 1C, 3C, and 5C. The battery cell have a typical capacity of 40 Ah, so it means that at 1C rate the discharge current is 40A, 120A for 3C and 200A for 5C. Here, the inlet air velocity is fixed at 3 m/s at ambient temperature. The same type of temperature evolution is also observed by Kim et al. (Kim et al. 2009). This shows that the battery temperature is much infected by the amount of discharge rate. Higher discharge rate generates more heat and thus increases the temperature.

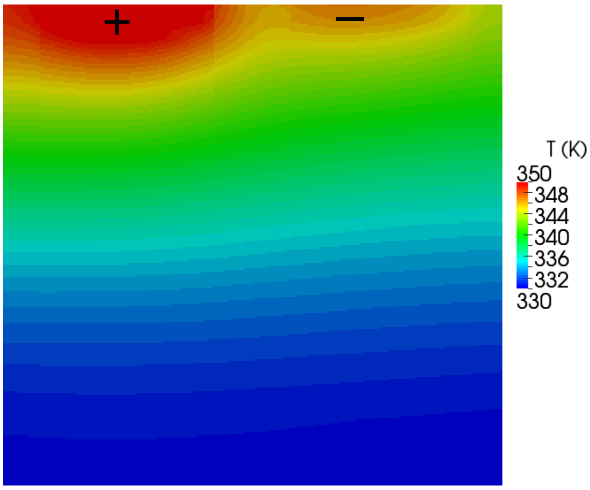


Figure 8: Surface Temperature of Battery Cell

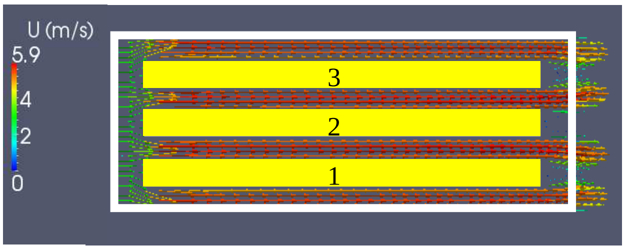


Figure 9: Air Flow between Battery Cells in the Battery Pack

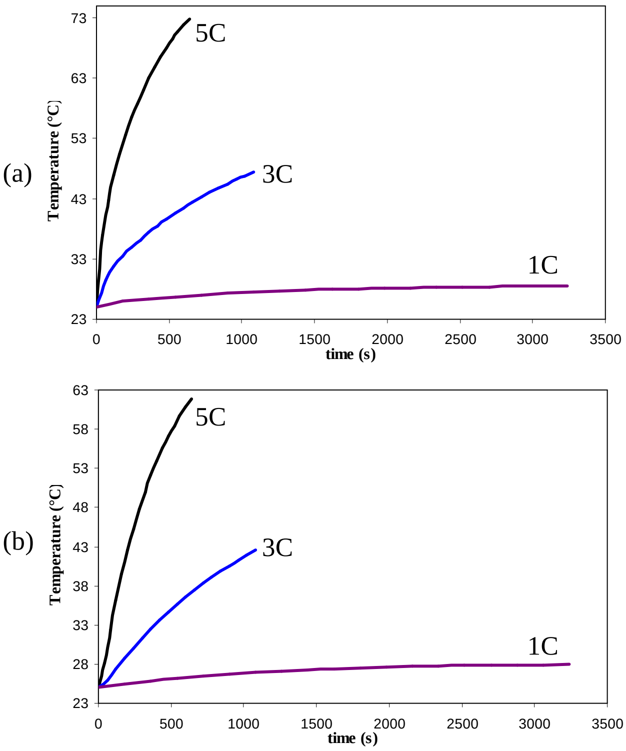


Figure 10: Cell Surface Temperature (a) at Point A and (b) at point B for Different Discharge Rate

To see the effect of cooling system on the battery temperature, we have run a set of simulation with 3 different cooling air initial temperatures which is the ambient temperature, 15°C and 5°C. At the same time the air inlet velocity is maintain at 3 m/s, and the discharge rate is fixed at 5C. Figure 11 shows the surface temperature evolution of 1st cell at point A for different cooling air temperature. It shows a strong increase of temperature at the beginning of discharge process for all three cases. Higher cell surface temperature increase is observed at higher cooling air temperature. By using cooling air at ambient temperature, the cell surface temperature increase to more than 70°C at the end of discharge process, which is over the save working limit of battery. This shows that at higher discharge rate (5C), the cooling air of 3 m/s at ambient temperature is insufficient to keep the battery in save working region. An additional cooling is needed for this purpose.

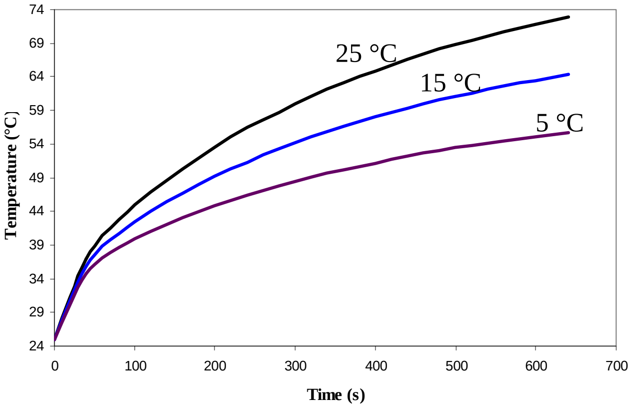


Figure 11: Cell Surface Temperature at Point A with Different Cooling Air Temperature

4. CONCLUSION AND PERSPECTIVES

A thermo-electric modelling of a lithium ion battery for automotive applications is presented. An electric equivalent description including temperature dependence is implemented in OpenFOAM, an open source CFD software, providing the possibility to link thermal losses inside the battery cells to forced convection of an air stream. The simulation results confirm observations from experimental results were the temperature is higher close to the connectors. Also there is a strong link between the discharge rate and the temperature decrease.

In the following the theoretical studies will be continued with regard to different aspects like air velocity and validated using experimental results, before drawing conclusions toward the improvement of the cooling of lithium ion batteries for automotive applications.

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AUTHORS BIOGRAPHY

CHE DAUD zul hilmi received the B.Sc degree in Mechanical (automotive) Engineering from University of Technology Malaysia (UTM), Johore, Malaysia, in 2007 and the M.Sc. degree in Mechanical Engineering from University of Burgundy, Nevers, France, in 2011. He is currently working toward his Ph.D. degree in Mechanical Engineering from University of Burgundy, Nevers, France. His research area is in the development of hybrid vehicle model with focus on the thermo-electrical characteristic of the battery cells and the battery pack.

Daniela CHRENKO (M'09) received the Dipl-Ing. FH degree in applied physics of the university of applied sciences in Wedel, Germany in 2002, the MSc of process engineering at the university of applied sciences in Hamburg Germany in 2006 and the PhD for the study of onboard hydrogen production for low temperature fuel cell systems at the university of Franche Comté in Belfort, France in 2008. Her research is linked to technologies for automotive applications, namely fuel cell systems. She worked on Stirling engines in combination with high temperature fuel cell systems, activities are carried out at the université of Franche Comté. The aime of her research is to increase energy efficiency in transportation applications. She is now working as associate professor at the University of Burgundy.

Fabien DOS SANTOS holds an engineering degree from Institut Supérieur de l'Automobile et des Transports, France in 2004. In 2012, he received his PhD for his numerical study on engine injectors, with a focus on cavitation and needle movement inside the nozzle, at the DRIVE laboratory of the University of Burgundy, France. The aim of his research is to understand the flow formation inside an injector nozzle (for automotive applications) and its influence on the liquid atomisation. He is now working as teaching assistant at the University of Burgundy.

Dr. El-Hassane AGLZIM received in 2004 the "DESS" degree (specialized graduate degree) in embedded electronics systems from the University of Metz, France. In 2005, he received the M.Sc. degree science engineering, from the University of Nancy, France. In October 2009 Aglzim obtained the Ph.D. degree in the Instrumentation and Microelectronics (IM) Science at the University of Nancy. His Ph.D. thesis was entitled 'Characterization by electrochemical impedance spectroscopy method of the complex impedance of a fuel cell - evaluation of the influence of humidity'. From 2009 to 2010, he completed a PostDoc in the System and Transportation Laboratory (SeT) in Belfort, France and he joined the Energetic team of the ISAT in September 2010 as an associate professor. His current research interests the diagnosis of fuel cells by using the Impedance Spectroscopy method and the control strategies on HEV vehicles.

Prof. Luis LE MOYNE received the Engineer diploma in 1992, and PhD in 1997 from Arts&Métiers-Paritech. His research experience of 15 years is related to different aspects of automotive engines and powertrains energy efficiency.