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Development of a Thermal Model for Lithium-Ion Batteries for Plug-In Hybrid Electric Vehicles

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Abstract

This paper describes a novel thermal model for lithium-ion battery technology. The model has been developed in Matlab/Simulink, which is based mainly on the electrical parameters such as thermal resistance, thermal capacitance, and thermal convection. In this study, a new methodology is presented for extraction of the model parameters based on the Matlab/Simulink parameter optimization tool.
The results exhibit that the error percentage between the simulated and experimental results is less than 5%. According to this model, the battery cell temperature can be kept in a safe operating region by coupling the surface temperature of the battery with the heating and cooling systems. This will allows to enhance the battery performances on one hand and to avoid thermal runway effect on the other hand.
The proposed battery model is not only useful for pouch battery cells but can be employed for any battery design concept.

Keywords: Thermal management, simulation, lithium battery, HEV, BEV

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) [1,2]. However, the battery technology, which can be used in these applications are very limited due to their limitation in the energy and power capabilities [1,2].
In the last decade, lithium-ion battery technology has acquired considerable high attention due to the beneficial performances in the term of energy, power and life cycle [3,5]. However, from the thermal point of view, lithium-ion batteries can be considered as critical [5-7]. Especially for the chemistries lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminum oxide and lithium cobalt oxide [5-7]. In addition, the performances of this battery technology are strong temperature dependent as shown in Figure 1.

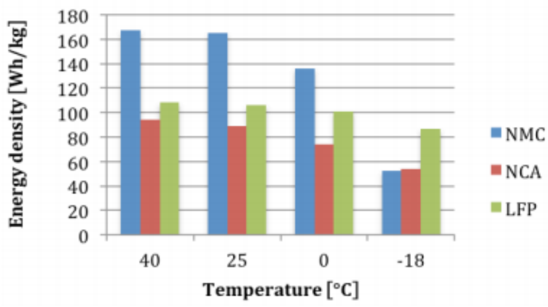

Figure 1. Energy density of various lithium-ion chemistries

In order to keep the lithium-ion battery cells in the desired temperature window, a cooling and a heating system are required. However, the operation of these two systems is depending on the battery cell skin temperature. Therefor there is a need for an accurate thermal model, which should predict the surface temperature under all environmental conditions. In [8], Al Sakka et al, proposed a thermal model, which has been developed for cylindrical Electric Double-Layer Capacitors (EDLC), by performing specific technique on the material level. In [9], Forgez et al, have developed a methodology for simulation of the inside temperature of a cylindrical lithium iron phosphate battery cell. However only the surface temperature has been measured. In [10,11] a series of electrical lithium-ion battery cell models are presented for prediction of the relevant performance. In these papers, the high importance of the surface temperature impact on the electrical parameters is highlighted. Therefore, from this point of view, there is a need for an accurate lithium-ion thermal model on cell level.

In this paper, a new thermal model is developed that can be used for lithium-ion batteries or any battery technology such as nickel-metal hydride/VRLA. The model has been developed in Matlab/Simulink SimPower System with high degree of integration in BMS.

2 Mathematical analysis

Generally, the heat distribution inside a battery cell can be described by equation (1). As it is presented, the equation is written in a Cartesian coordinate system. Where ρ is the density of the cell (kg/m^3), C_p the specific heat capacity (J/kg.K), k_x, k_y and k_z represent the coefficient of the thermal conductivity (W/m^3) in the x, y and z directions, respectively, which varies with time and the location. Q_n is the heat transfer flux

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)\pm I\left(T\left[\frac{dE}{dT}\right]\right)+I(E-V)=m.\rho.C_p\frac{\partial T}{\partial t} \quad (1)$$

In the framework of this study, only the temperature distribution in the radical direction will be considered, because, the surface temperature is the only parameter that physically can be measured by using a thermocouple. Hereby, from the thermodynamic standpoint, the heat balance inside the cell can be modified as follow:

$$m.\rho.C_p.(T_s-T)=-I\left(T\left[\frac{dE}{dT}\right]\right)+I(E-V) \quad (2)$$

The first term $-I.\left(T\left[\frac{dE}{dT}\right]\right)$ is the generated heat because of the reversible entropy change. While $I.(E-V)$ represents the heat generation caused from the ohmic resistance.
For development of a thermal battery cell model, the main parameters that will be considered are the specific heat capacity, thermal capacity and thermal resistance. The model has been developed based on the assumption that the heat development in the battery is homogenous.

3. System description

The extraction of the thermal model parameters needs dedicated experimental investigation systems such as impedance spectroscopy or climate chambers. In the framework of this study, a load profile has been employed by using a battery tester of PEC CORPORATION type SBT 0550. This tester allows employing constant and pulsing load profiles. In order to keep the environmental temperature of the battery constant, the battery cell has been placed in a climate chamber (CTScompany) as presented in Figure 2.

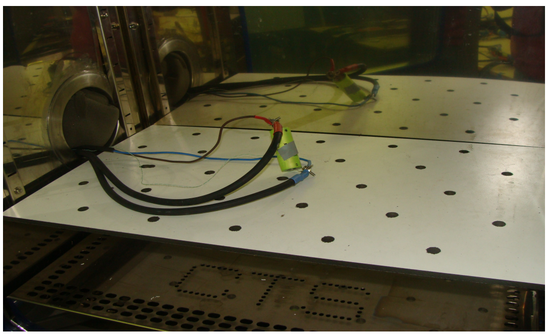

Figure 2. Climate chamber

The battery cell that has been used in this study is coming from A123 Systems. The battery has a capacity of 3.2Ah and the nominal voltage of the cell is 3.3V. Furthermore, the cell has high rate and power capabilities, which makes it very useful for HEV applications.

Figure 3. Investigated battery cell

4. Parameter extraction

As documented in the introduction, the modeling of thermal behavior of battery cell can be performed in different ways. The most used methodology is based on Computational Fluids Dynamics (CFD), multiphysics simulation tools such as COMSOL and Phoenics [12-15]. However, these tools need many parameters for accurate estimation of the thermal characteristics of a battery. The proposed parameters can only be obtained by using complicated and electrochemical characterization tests, which can be carried through dismantling the battery cell. Due to these reasons, in the framework of this study, a thermal model is developed based on electrical characterization tests. The proposed model enables the prediction of the battery surface temperature under any condition.

However, prior to start with modeling, the battery parameters such as thermal resistance, and thermal capacitance should be derived. In [9] is reported that these parameters are the most decisive characteristics for secondary rechargeable energy storage systems. However, Al Sakka et al. mentioned that the thermal convection is an important parameter that should be included in any kind of thermal model [8].

In the framework of this study, an estimation routine has been developed for extraction of the model parameters.

In order to be able to extract these parameters, the micro cycle load profile as presented in Figure 4 has been implemented. Such micro cycle has been repeated until the thermal steady state condition of the battery cell has been achieved. Then, the analysis has been extended to different current rates (4 I_t,6 I_t,8 I_t,10 I_t) and at state of charge levels (80%, 65%, 50%, 35%, 20%). All these tests have been carried out at 25°C working temperature.

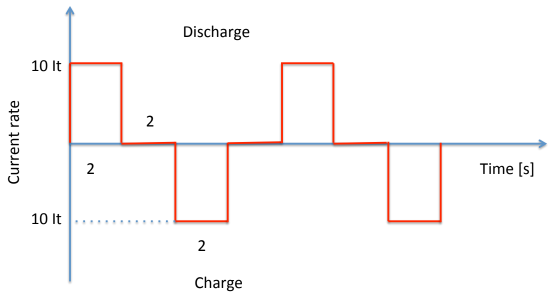

Figure 4. Implemented load profile

Figure 5, Figure 6 and Figure 7 exhibit the evolutions of thermal convection, thermal resistance and thermal capacitance versus state of charge at different current rates. In Figure 5 is illustrated that the convection evolution in function of state of charge is not an unambiguous value. This parameter is slightly depending of the SoC and current rate. It varies between 3 and 3.5 °C/W. The same evolution is remarkable for the thermal resistance, where the value changes between 3.2 and 4 °C/W. These results are in contradiction with what has been observed for EDLC [8]. The value for EDLC in the temperature range 50°C and 10°C can be assumed as constant. Then in Figure 7 in indicates that the thermal capacitance of the battery proposed battery is almost constant with exception at 4 I_t between 30 and 50% SoC, where the value seems significantly higher. In order to include the appropriate value at a certain condition, a multidimensional look-up table have been used.

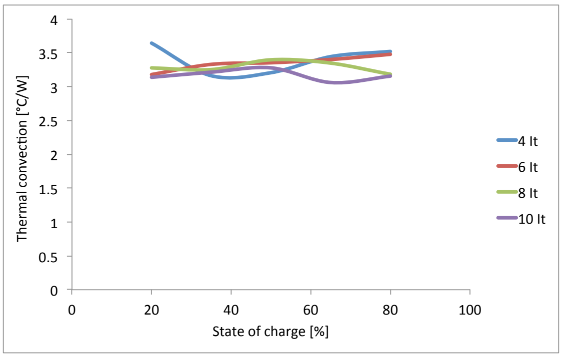

Figure 5. Evolution of thermal convection resistance versus state of charge

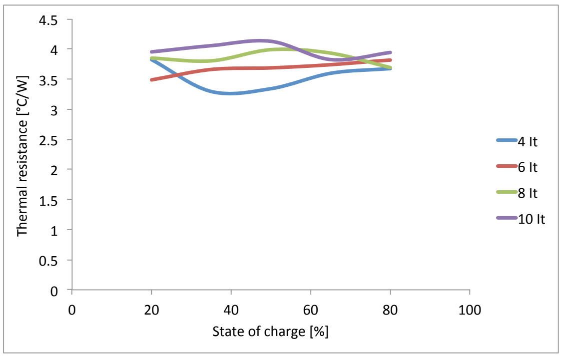

Figure 6. Evolution of thermal resistance versus state of charge

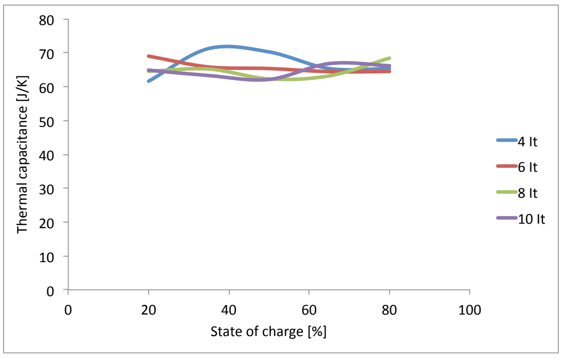

Figure 7. Evolution of thermal capacitance versus state of charge

5. Results and discussion

In order to verify the developed thermal battery model, series of comparisons is made based on simulation and experimental results. This first test is presented in Figure 8. As we observe, the model is in good agreement with experimental results. The error percentage based on this test is in the range of 0 – 1°C.

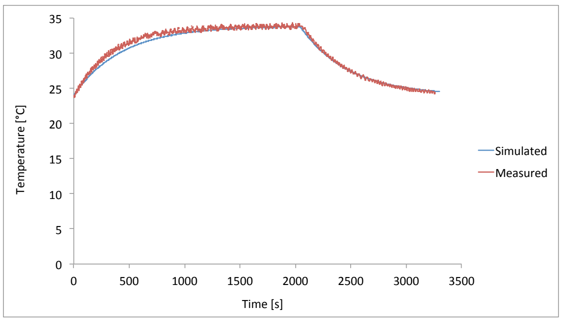

Figure 8. Comparison of simulated and measured at 25°C working temperature

In the previous test, the model has been compared with experimental results based on the same load profile as suggested in Figure 4. However, there is a need for validation step to evaluate the performances and accuracy of the developed battery model at other conditions without to perform any calibration in the model.

In Figure 9 a validation test has been carried out at room temperature about 24°C.

The corresponding simulation and experimental comparison are illustrated in Figure 10. Here again, we recognize that the high accuracy of the battery model against the experimental results. Based on these results, we can conclude that the developed battery model is able to predict the surface temperature of the battery cell with significantly low error percentage.

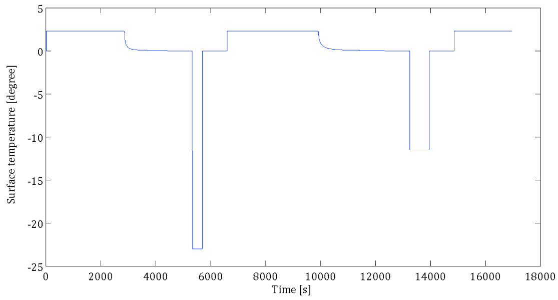

Figure 9. Load profile for validation

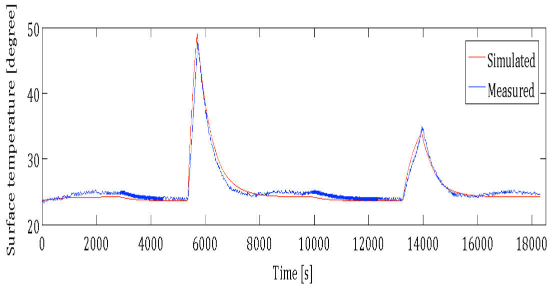

Figure 10. Comparison of experimental and simulation results at room temperature (~24°C)

Finally in Figure 11 another example is illustrated based on dynamic discharge performance test as described in the standard IEC 61982-2 [16]. For this test only the value for the thermal convection has been adjusted (8 °C/W). At room temperature, the natural air convection is applicable. Unlike to the tests in the climate chambers, the convection is more forced rather than natural. In Figure 11, we recognize the high performance of the battery model. According to the simulated and experimental results, the error varies between 0 – 1°C.

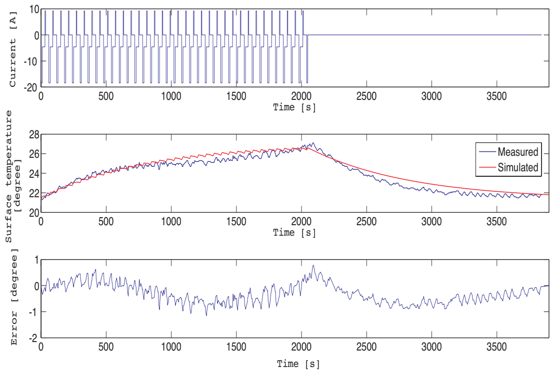

Figure 11. Comparison of experimental and simulation results at room temperature (~22°C) based on DDP test

Thus, according to these results, a thermal sensor in real application can be avoided. The output if the model can further be used as an input in the electrical model where the model parameters are in function of temperature.

6. Conclusions

In this paper, an advanced thermal lithium-ion battery model is developed on cell level. The model enables to predict the battery surface temperature at any working conditions. According to the presented results, the simulation results are in good agreement with experimental results.
Moreover, this study proposed an estimation routine for determination of the model parameters.
The model has been developed particularly for cylindrical battery cells; however it can be applied for another battery cells design.
It should be noted that the model assumes that the surface temperature is uniform. However, this assumption does not reflect the battery cells behavior in the reality. The battery cell is mostly subjecting to various local temperatures. In order to take this issue into account and to have a clear view of the temperature gradient inside the battery cell, there is a need for a three-dimensional battery model. Such models will be performed in the near future by using multiphysics simulation tools such as ANSYS and COMSOL. The results of the both approaches will be compared and analyzed.

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