

Lithium Ion Capacitor – Optimization of Thermal management from Cell to Module Level

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Summary

This paper represents the thermal behaviour of an energy storage system based on advanced lithium-ion capacitors. In the proposed study, an extended statistical analysis has been performed for evaluating the main thermal parameters. Based on the performed analysis, an electro-thermal model and a 3D thermal model have been developed for optimization of the thermal management strategy.

The models have been developed for a 2300F lithium ion capacitor cell. The developed models are in good agreement with the experimental results, which indicates that the models can be used for the design and optimization of the thermal management.

Keywords: Lithium ion capacitor, Thermal management, Modeling, Power

1 Introduction

Since the beginning of the automobile era, the internal combustion engine (ICE) has been used for vehicular propulsion. In addition, motor vehicles powered by the ICE are significant contributors to air pollutants and greenhouse gases linked to global climate change [1, 2]. As the global economy begins to strain under the pressure of rising petroleum prices and environmental concerns, research has spurred 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) [3,4]. No current battery technology can cope with the following, often concurrent but necessary, criteria in the automotive industry: supporting the output power during acceleration, efficiently use the available regenerative energy and has a considerable life cycle [4-12].

A possible solution for enhancing the present battery performances is the hybridization of batteries by using EDLCs [13-14]. However, such a hybrid architecture needs an expensive and high efficient DC-DC converter. This makes this combination less attractive in mobile applications where cost, weight and volume can be considered as main barriers [14].

In order to overcome these obstacles, during the last 10 years several types of advanced rechargeable energy storage systems have been developed by many companies and research centers, called lithium ion capacitors (LIC) or hybrid capacitors [15-20].

In [21-24] the general performances of this technology has been investigated and they observed that an energy density of 14 Wh/kg and over 10000 W/kg can be achieved. In [25-28] the suitability of the proposed technology have been analyzed and prove that lithium-ion capacitors can act as a main power or energy source without any reduction of the system capabilities. Furthermore, the LICs seem in a certain sense more attractive than EDLCs due to the higher maximum operating voltage of 3.8V compared to 2.7V for EDLCs. This implies that less cells need to be connected in series to achieve the desired voltage level, which will result in a decreased complexity of the entire system. However, the existing knowledge of the LIC technology and in particular the thermal one is not clearly known. Therefore in this article the thermal characteristics of LIC technology from JM Energy will be studied in depth. The characteristics of the proposed LIC cells are:

- Capacitance: 2300F,
- Nominal cell voltage: 3.3V,
- Cell weight: 300 g.

2 Model cell development

2.1 Geometry features and material properties

The cell is composed of three domains: the electrode domain, the negative and positive tabs as shown in Figure 1. These domains are made from different materials. The positive and negative tabs are made of Aluminium and Copper, respectively. The electrode domain is assumed to consist of several cells layers of anode, cathode, separator and electrolyte. Therefore, the thermal conductivities are anisotropic in these areas, with a higher value along x and z-directions, than the normal x-direction to the layers. Furthermore, the thermal conductivity along y-direction is the same as the z-direction. Therefore, an equivalent material is set up to model all different layers that consists the cell.

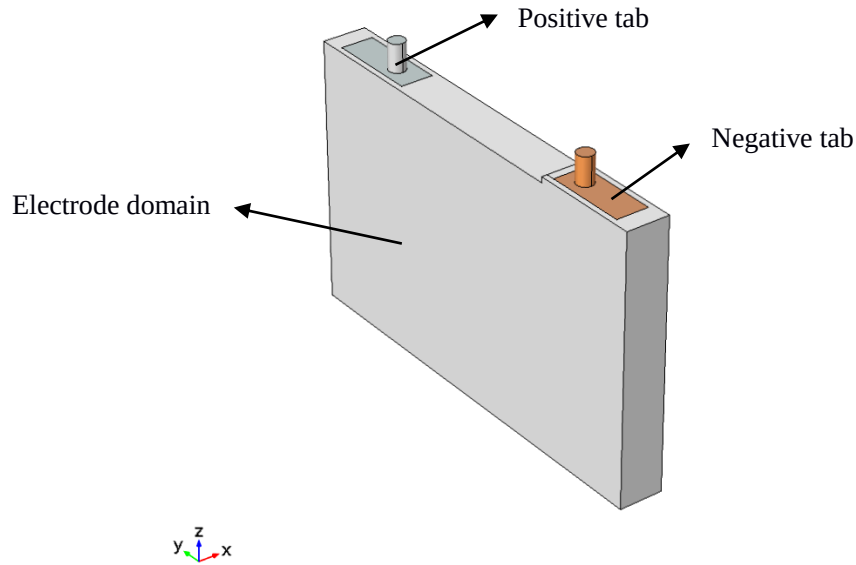


Figure 1. Geometry representation of the LIC Cell

2.2 Model development

A transient heat equation is used to describe the thermal distribution in the LIC cell, where the amount of generated heat must be stored inside the cell or transferred from the cell to its surrounding.

$$\rho C_p \frac{dT}{dt} = \left[\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} \right] + \dot{q} \quad (1)$$

Where $\dot{q}$ (W/m³) and T(K) denote the heat source and the temperature of the cell, respectively.

The heat flux transferred from the cell to its surroundings is expressed as follow:

$$-\left[\lambda_x \frac{\partial T}{\partial x} + \lambda_y \frac{\partial T}{\partial y} + \lambda_z \frac{\partial T}{\partial z}\right]_{boundaries} = h(T - T_a)_{boundaries} \quad (2)$$

Where h (W/m².K) and T_a (K) denote the convective heat coefficient and ambient temperature, respectively.

The heat source in the electrode domain is computed from the Bernardi equation, where its simplified form can be expressed as follow [29]:

$$\dot{q} = I(U - V) - IT \frac{\partial U}{\partial T} \quad (3)$$

Where I (A) resembles the current flowing through the battery, U (V) the open circuit voltage of the cell and V (V) the terminal voltage of the cell and $\frac{\partial U}{\partial T}$ (V/K) the entropy coefficient.

The heat source of the tabs is computed through this relation:

$$\dot{q} = \frac{RI^2}{V_{tab}}; \quad R' = \rho' \frac{l}{S} \quad (4)$$

Where R' (Ω), I (A), V_{tab} (m³), ρ' (Ω m), l (m), and S (m²), are the electrical resistance, current rate, volume, resistivity, length and cross-section of the associated tab, respectively.

2.3 Input parameters

This model requires as inputs the heat sources ($\dot{q}$), the thermal parameters (conductivity ($\lambda_x, \lambda_y, \lambda_z$), density (ρ), heat capacity (C_p) and the convective heat coefficient (h) of each material domain. The heat source at the electrode domain, the thermal conductivity in the x-direction, the heat capacity and the convective heat coefficient are taken from the earlier 1D electro-thermal model developed in Matlab Simulink, see section 2.3.1. Therefore the thermal conductivities in the other directions (y,z) were calculated in order to represent as much as possible the thermal behavior given by the thermal camera.

2.3.1 Parameter extraction

The extracted outputs from the Matlab Simulink model are shown in Table 1.

Table 1. Input parameters from Matlab-Simulink model

Parameters	Function name	Units
(Time, Current)	Inp	(s, A)
(Time, Thermal Capacitance)	Capacitance	(s, J/K)
(Time, Conductivity)	Resis_cond	(s, W/m.K)
(Time, Convective coefficient)	Resis_conv	(s, W/m ² .K)
(Time, Heat source)	heat_source	(s,W)

3 Results

3.1 Parameter extraction from Matlab-Simulink model

Figure 2 and Figure 3 show the applied load profiles, with a continuous charging and discharging of the cell between its voltage limits at room temperature. The thermal parameters are extracted according to the cell type and load profile from the validated 1D Matlab Simulink model. Figure 4 to Figure 6 show a typical example of the 2300F cell thermal parameters based on the applied load profile 1. Among the different thermal parameters, one can find the heat source the thermal capacitance and the conductive and convective thermal resistances.

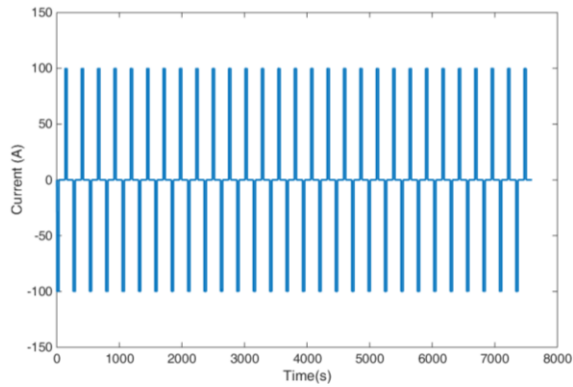


Figure 2. Applied load profile 1

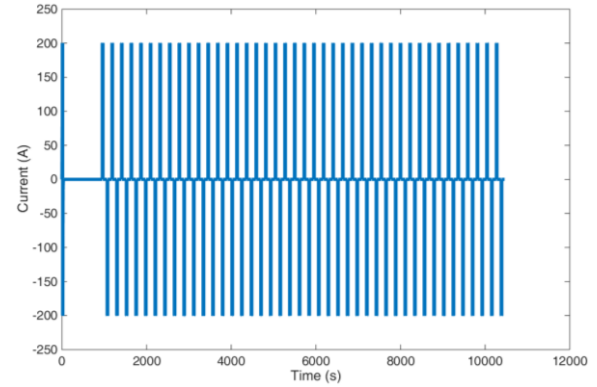


Figure 3. Applied load profile 2

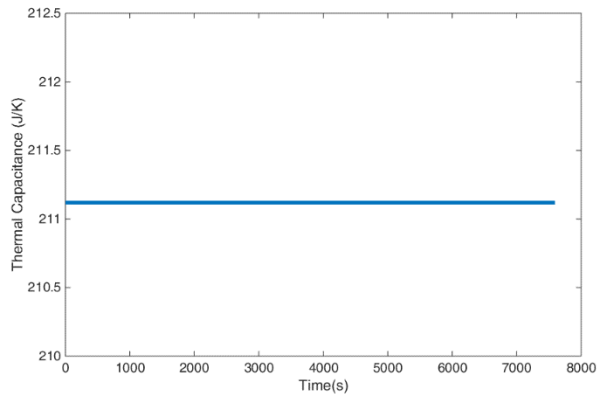


Figure 4. Thermal capacitance of the cell from Matlab Simulink model based on the applied load profile 1

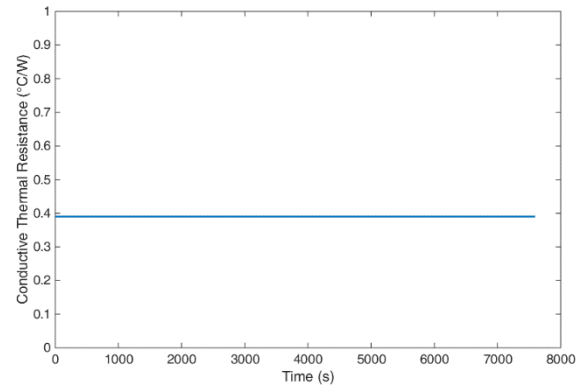


Figure 5. Conductive thermal resistance of the cell from Matlab Simulink model based on the applied load profile 1

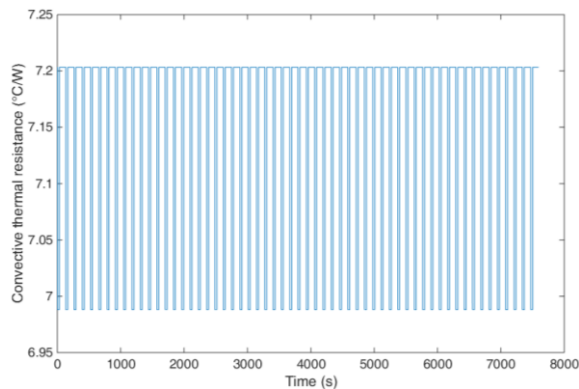


Figure 6. Convective thermal resistance of the cell from Matlab Simulink model based on the applied load profile 1

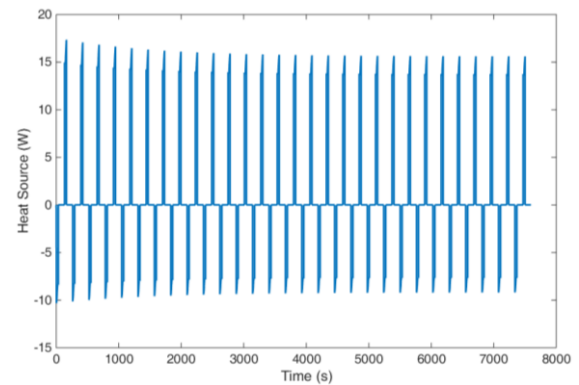


Figure 3. Heat source of the cell from Matlab Simulink model based on the applied load profile 1

3.2 Validation of the developed 3D thermal model

Three-dimensional thermal models are usually implemented in CFD and FEM commercial software packages such as ANSYS, COMSOL Multiphysics, etc. Generally, these models are used for predicting the temperature distribution throughout the cell at different environmental conditions. This shows the high importance of sizing the cooling and heating units. Despite, its good accuracy, the implementation of CFD models require an immense effort on meshing and time computation.

In this study, the model implementation and some results of the 3D thermal modeling using the commercial software package Comsol Multiphysics are described and discussed. The approach which is used, is based on the coupling of the thermal and the electrical models.

With the different inputs (thermal parameters and applied load profile), the thermal behaviour of the LIC cell has been simulated using the second load profile as described in Figure 2. The accuracy of the calculation depends heavily on the mesh and the solver. A tetrahedral mesh is used in this study as can be seen in Figure 8. The thermal conductivity along y and z-directions has been tuned in order to match the temperature distribution. The 3D model has been validated experimentally by comparing the temperature measured by the thermocouple placed at the center of the LIC cell to the temperature simulated by the 3D model.

The developed model has been validated based on a set of experimental results at room temperature (about 25°C).

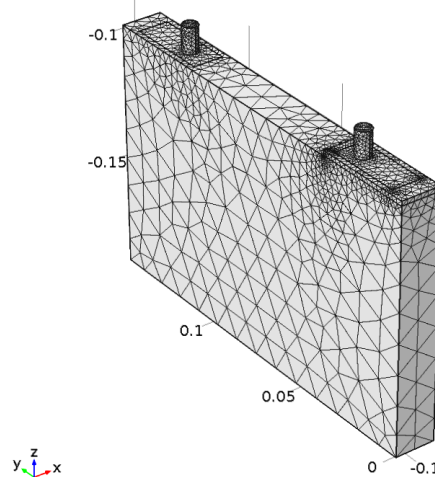


Figure 4. Meshing of the Cell

A good match is found between the experimental and simulation, with a relative error of globally less than 10%. Here it should be noted that the difference between the simulation and experimental values are less than 1°C based on Figure 5, which indicates the high accuracy of the developed model. In Figure 6 the error is slightly higher due to the different initialization temperature.

It can be seen from the Figure 5 and Figure 6 that the surface temperature increases during the discharge, while it decreases during the charge due to the high endothermic heat source.

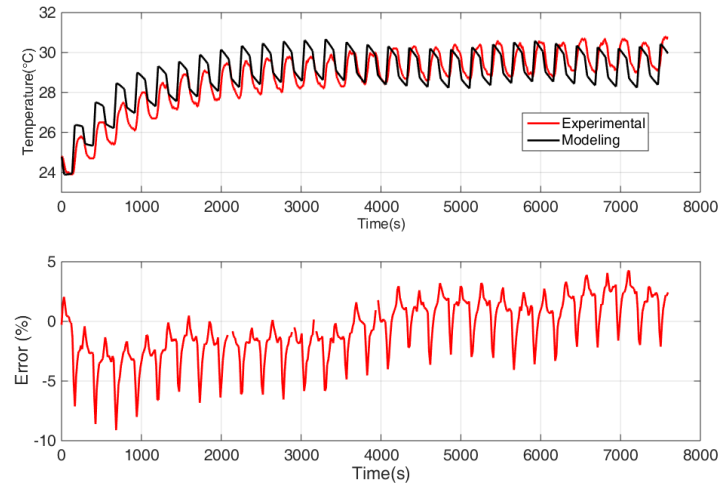


Figure 5. Comparison between 3D model and experimental data based on the applied load profile 1 for the 2300F cell

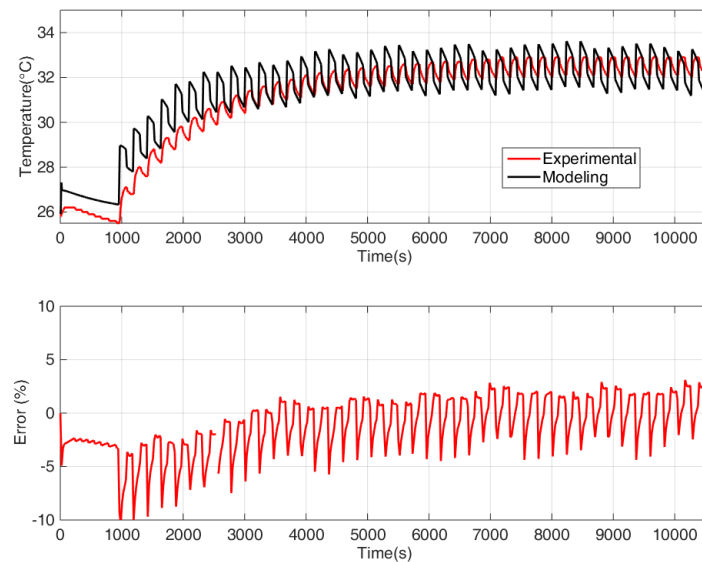


Figure 6. Comparison between 3D model and experimental data based on the applied load profile 2 for the 2300F cell

3.3 Thermal imager validation

The full thermal distributions at different time steps, applied load profiles and LIC cell type are compared to the thermal imager measurement and show a good agreement as shown in Figure 7. This indicates that the LIC cell surface temperature is nearly uniform, except in the middle where the maximum temperature is located during discharge.

However, during charge, the maximum is located near the positive tab because the generated heat at the positive tab is higher than the negative tab due to the higher resistance of the Aluminum.

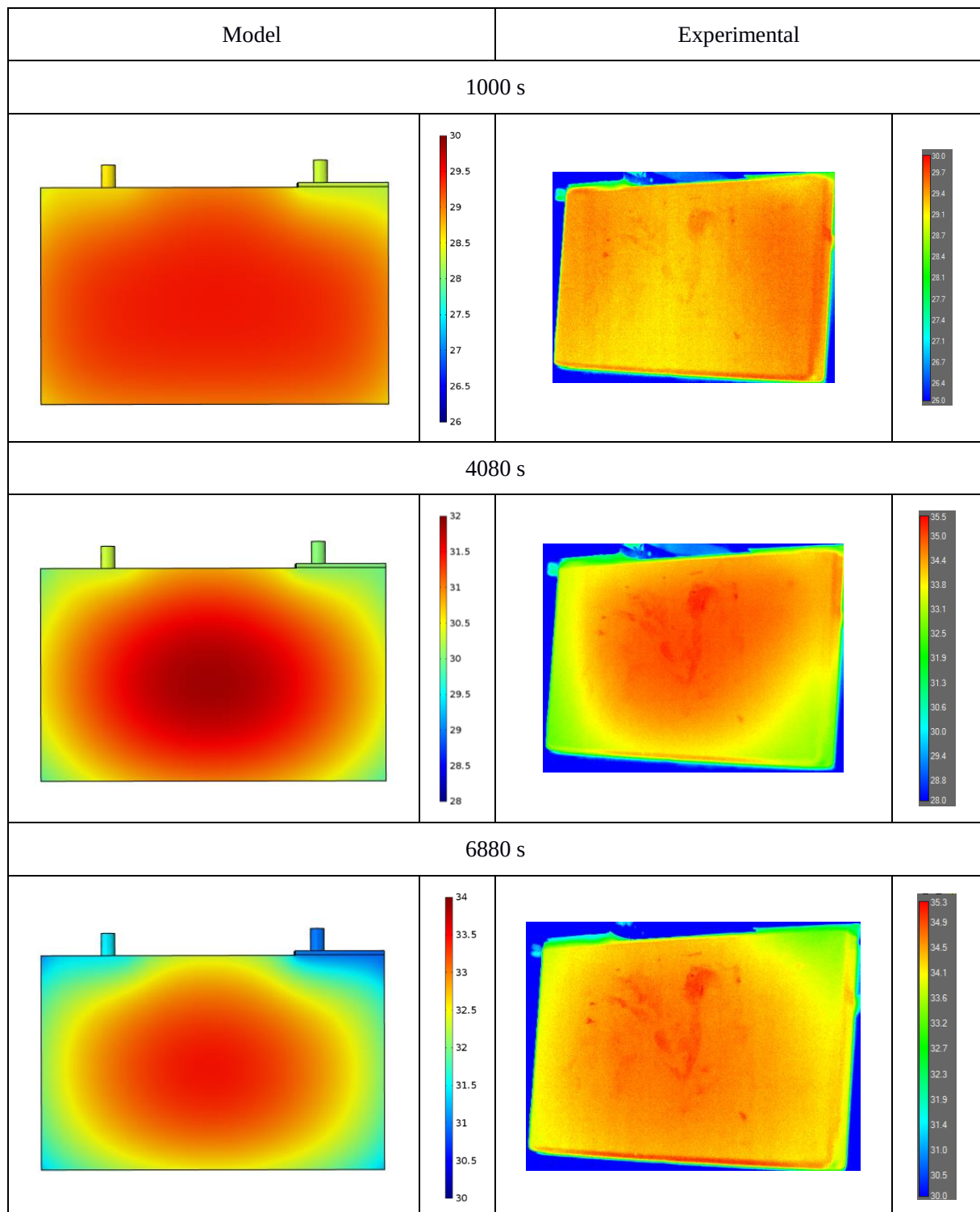
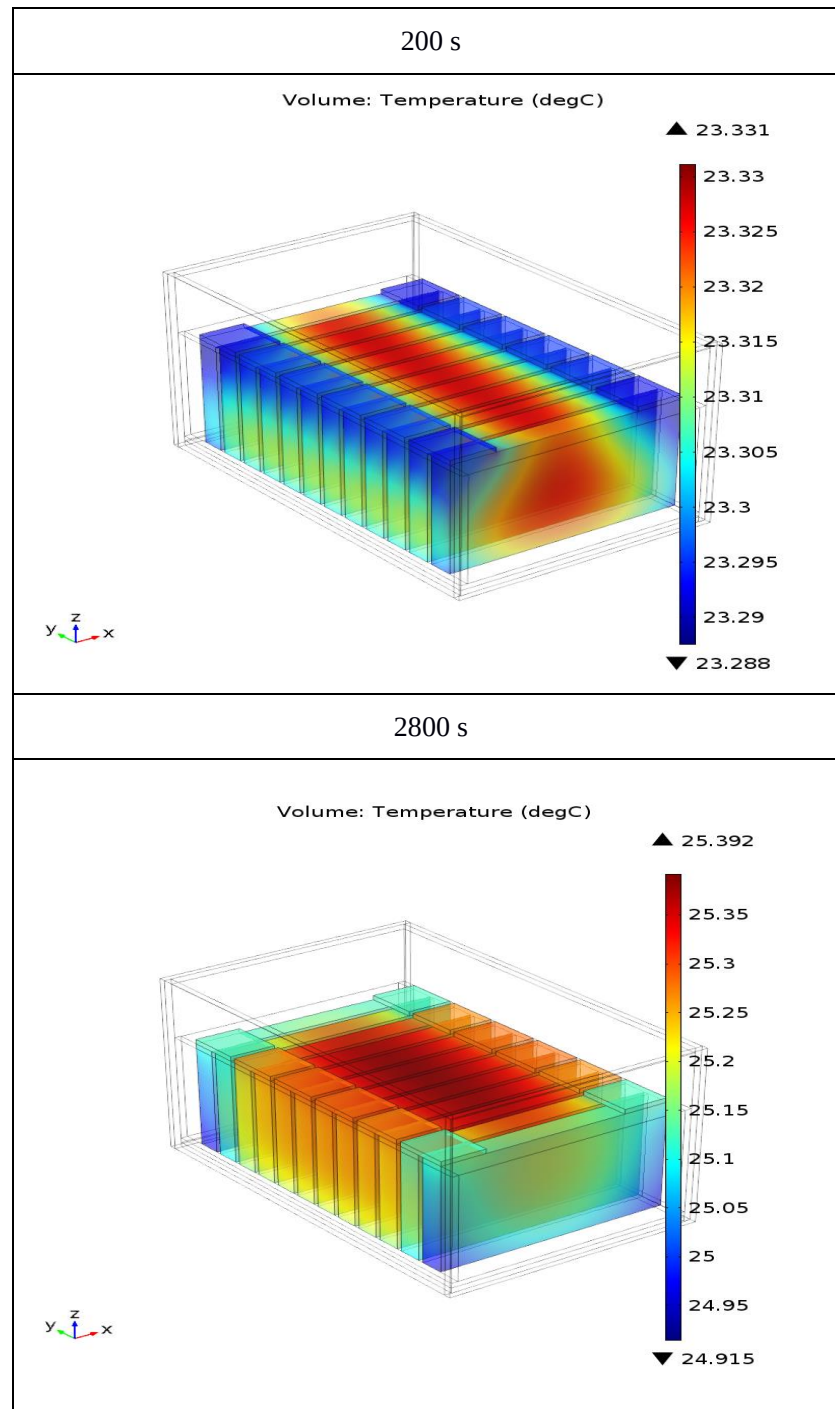


Figure 7. Comparison between 3D model and thermal camera images at different time steps for the 2300F cell based on the applied load profile 2

4 Thermal module model for optimization of thermal management

Following the 3D thermal model that has been developed in section 3, in this section the model has been extended to module level 48V (12 cells in series). In Figure 8 one can observe the evolution of the temperature in the module. It is remarkable that during the tests the temperature increase is more located at the middle of the module. This means that this is the critical point. From the thermal management point we can indicate that passive air-cooling will not be enough to have a homogenous temperature distribution. This results to the fact that the developed model can be used to optimize the thermal management of the investigated module by considering other cooling concepts such as active air cooling, liquid cooling and cooling based on phase change materials combined with active air-cooling.



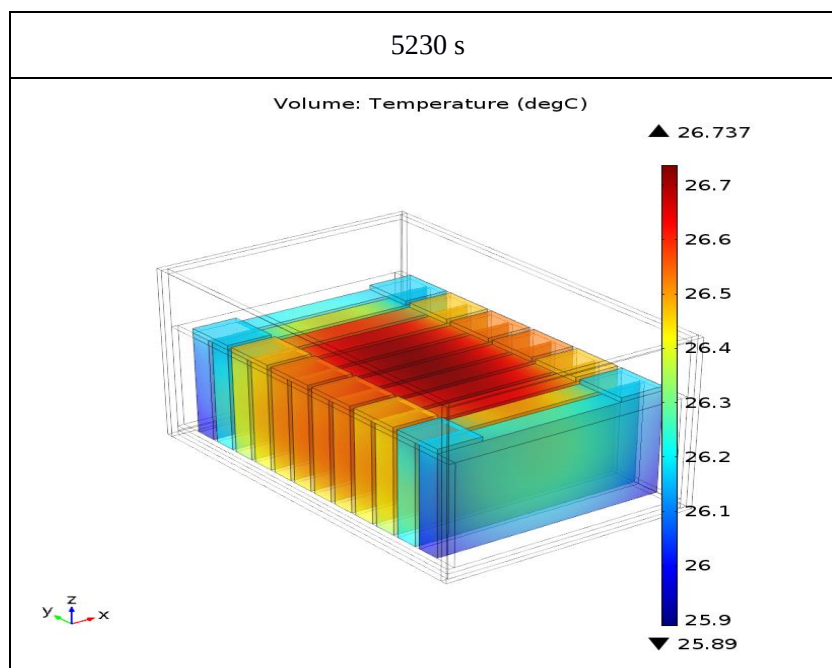


Figure 8. Comparison between 3D model and thermal camera images at different time steps based on the applied load profile 2

5 Conclusions

In this deliverable, an extended simulation analysis has been performed for 2300F lithium-ion capacitors cells based on a 3D thermal simulation tool in Comsol Multiphysics. The thermal study shows that the simulation results for the proposed LIC cells are in good agreement with the experimental results. The error is max. 2°C. In addition, a dedicated thermal model at a module level (48V) has been developed. The model allows optimizing and sizing the thermal management of the module to enhance the module performances and lifetime.

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Prof. Dr. Peter Van den Bossche promoted in Engineering Sciences from the Vrije Universiteit Brussel on a thesis “The Electric vehicle, raising the standards”. He is currently lecturer at the Vrije Universiteit Brussel. Since more than 15 years he is active in several international standardization committees, currently acting as Secretary of IEC TC69. He has been closely involved in electric vehicle research and demonstration programmes in collaboration with the Vrije Universiteit Brussel and the international associations AVERE and CITELEC, and is now coordinating research projects on battery modeling, always observing the link to standardization development in the field.



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 (<http://mobi.vub.ac.be>). 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).