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Liquid Thermal Management of a Lithium-ion Capacitor Module

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Summary

This paper presents the development of a thermal management system for an energy storage system based on lithium-ion capacitors. In the proposed study, a liquid cooling method for a LiC module that comprises 12 cells has been investigated. In this sense, a 3D thermal model coupled with liquid cooling plates has been developed in order to test its effectiveness and the potential it could represent in comparison with other cooling strategies. The developed model has clearly shown an optimal performance of the module could not be reached without controlling the temperature distribution, using liquid-cooling medium, it is possible to solve this issue.

Keywords: lithium-ion capacitor, thermal management, 3D-modelling, power applications.

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1 Introduction

In the past few years, research about energy storage technologies has become key in the fight against climate change due to the unstable outcome of the renewable energy sources. More sustainable eco-friendly changes need to be made on each level and in each sector. Particularly, the automotive industry that uses as main way of transport, the internal combustion engine (ICE) has to innovate. Various types of clean energy transportation systems using lithium-ion batteries (LiBs) for propulsion such as hybrid-electric vehicles (HEVs), battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) have emerged [1], [2]. Unfortunately, few current provide an efficient source of regenerative energy, ensure a high power output during acceleration and reliability considering a high life cycle [3], [4].

To solve the problems above, search of hybrid systems that combines the perks of high-power density and high-energy density such as: electrochemical double layer capacitors (EDLCs) and LiBs has been pursued. A literature survey indicates several dual-systems management strategies associating EDLCs with LIBs in one system for automotive applications [5], [6]. However, such a hybrid system needs an expensive and high efficient DC-DC converter. This would increase the lifetime of the cost, weight and volume of the system where actually they are considered as main barriers [7]–[9].

Instead of using two distinct systems, another technology has emerged call lithium-ion capacitors (LiCs). They deliver high energy and high power while assuring a long cycle life [10]–[12]. Indeed, their performances have have been investigated in and it was observed that an energy density of 14 Wh/kg and over 10000 W/kg can be achieved [13]. This compromise between high-power and high-energy comes from its composition which is inspired from the EDLCs and LIBs that provides an intermediate between both systems [14].

Nonetheless, since LiCs are meant for high-power applications, high-current and high-power are commonly applied in LiC battery cap, which results in an increase of the temperature inside the pack [15], [16]. This issue limits its operation if the battery pack is outside the optimal temperature range. Thus, a proper thermal model that is able to establish a thermal management strategy is required.

Therefore, it is necessary to provide a thermal management system that will keep its optimum performance. We proposed in this paper the development of a thermal model of a pack composed of 12 LiCs. Next, a thermal strategy is established. Among several cooling strategies, we chose liquid cooling which has better performances than active air-cooling [17]–[19]. In the following, a study of a LiC module coupled with a liquid cooling thermal management system is carried out as well as a discussion about the results and optimization of the parameters.

2 Model cell development

2.1 Geometry features and material properties

The LiC cell under this study is a lithium-ion capacitor of 2300F. The characteristics of the proposed LIC cell are given as follows:

Capacitance: 2300F,

Nominal cell voltage: 3.3V,

Cell weight: 300 g.

The cell is visible with its different domains in Figure1 and the dimensions of the element are 150 mm in width, 93.5mm in height and 15mm in thickness. These domains are made of different materials, namely: the electrode domain, the negative and positive tabs. The negative and positive tabs are made of copper and aluminium, respectively. Taking into account the thickness of the cell, 13 mm, the electrode domain is assumed to consist of several single layers, respectively, the anode, cathode, separator and electrolyte [20], [21]. Therefore, the thermal conductivities are anisotropic, with a lower value in the x-directions than the z- and y- directing resulting from the single layer assumptions [22], [23]. Additionally, the thermal conductivity along y-direction is the same as the z-direction, as reported in the literature. Thus, an equivalent material is set up to model the active material and the conductivities that consists the cell.

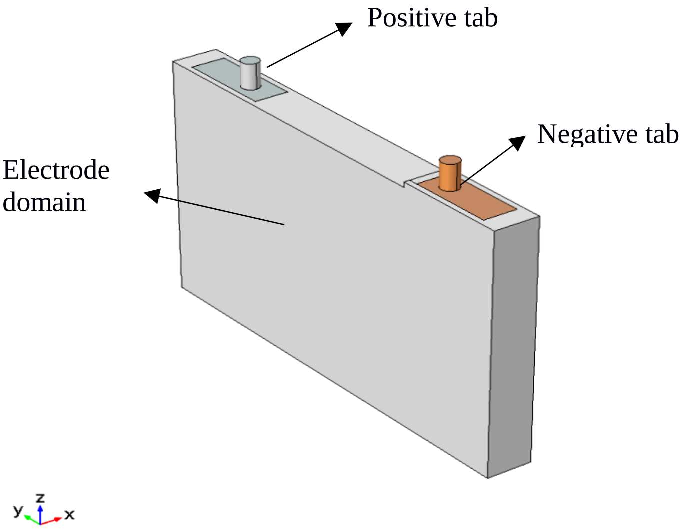


Figure1: Geometry representation of the LiC cell [24]

2.2 Cooling plate

The schematics of the cooling plate's design is represented in Figure2 and have the following dimensions: 150 mm in width and 100 mm in height. Taking into account the recommendation of the company, the cooling plate design is characterized with a thickness structure of maximum 6 mm with an inner copper channel diameter of 5 mm. The cooling channels and cooling plates are made of aluminium and copper, respectively. The cooling plates are located on both sides of the LiC.

The design of the inner channel is a typical design of cooling plate. It comprises one cooling channel having an inlet and outlet ends on the left and right sides of the cold plate, respectively. The intermediate portion with a sinuous pattern has arranged vertically. This design has the advantage of conducting the total flow rate into the cooling channel

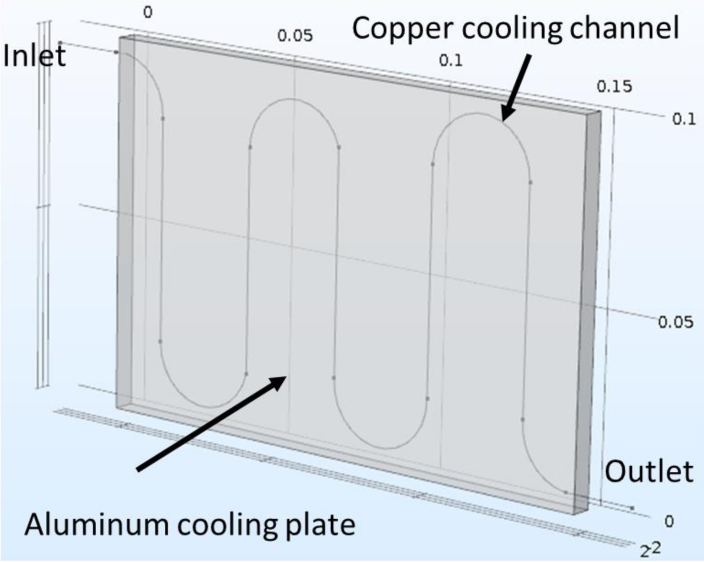


Figure2: Geometry representation of the cooling plate

2.3 Model development

In this section, the description of the model is presented. Due to the complexity of modelling cooling plates, computational fluid dynamics (CFD) commercial software package such as COMSOL Multiphysics is used to establish the three-dimensional thermal model. Despite, its good accuracy, the implementation of CFD models require an immense effort on meshing and time computation.

2.3.1 Battery domain

The energy balance equation of the battery cell is used to describe the transient thermal distribution in the LiC, where the amount of generated heat must be stored inside the cell or transferred from the cell to its surrounding can be formulated as [25]:

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

where q (W/m^3) and T (K) denote the heat source and the temperature of the cell, respectively. The convective heat flux transferred from the cell to its surroundings is calculated as follow [26]:

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

where T_a (K) and h (W/m^2.K) denote the environment temperature and the convective heat coefficient,

respectively. Since only natural convection is considered, in the model, the value of h was set to 5.
In the electrode domain, the heat source is derived from a simplified form of Bernardi equation [25]:

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

where I (A) represents the current flowing through the battery, U (V) the open circuit voltage (OCV) of the cell and V (V) the terminal voltage of the cell and $\frac{\partial U}{\partial T}$ (V/K) the entropy coefficient. In the tabs domains, the heat source is computed by this relation:

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

where R' (Ω), I (A), V_{tab} (m^3), ρ' ($\Omega\,m$), l (m), and S (m^2), are the electrical resistance, current rate, volume, resistivity, length and cross-section of the associated tab, respectively.

2.3.2 Cooling-plate domain

In the cooling-plate domain, the heat generated by the battery, is transferred to the cooling plates, and evacuated throughout the cooling channels. Taking into consideration the complexity to model the pipe circuit and the associated physic, the simulation of the heat transfer of the whole system requires a 3D geometry representation.

Nonetheless, modelling a 3D flow and heat transfer inside the cooling channels is computationally expensive. Thus, as the diameter of the cooling channel is small (5 mm), the flow and heat transfer inside the cooling channels can be modelled with a 1D pipe thermal-flow equations coupled with the 3D geometry of the cooling plates. In this specific domain, the energy equation is given by [26]:

$$\rho C_p \frac{dT}{dt} = \lambda \nabla^2 T \tag{5}$$

where λ(W.m^{-1}K^{-1}) is the thermal conductivity of the cooling plate , Cp(J kg^{-1} K^{-1}) is the specific heat capacity of the cooling plate, and ρ (kg/m^3): is the density of the cooling plate. For more details, readers are referred to the following work [27] for the numerical method describing the flow and heat transfer in the cooling channels .

2.3.3 Module model

In a previous paper [28], the electro-thermal model for a 2300F LiC has been established and validated by experiment. To continue further our research, in this study, a liquid-cooling featuring a LiC module is proposed. The battery pack is composed of 12 LiC (39.6V, 1.1Ah) connected in series.
To be able to compare the efficiency of the liquid-cooling strategy, a second module modelling without cooling system is proposed. As shown in Figure3, 12 cells are aligned in series to build the pack. In general, the heat is mainly generated by the LiCs within the electrode domain, tabs and connectors. The heat source of the connector can be neglected comparing to the heat generated by the tabs. In addition, due to its large size, the required amount of mesh for the connectors is huge therefore the connectors are not represented in this study. Based on this assumption, the module can be considered as a stack of 12 cells spaced by the length of the cooling plate. Then, the associated heat source is computed through equation (4).
Alternatively, the cooling plates have been placed between the cells in such a way that the heat is removed from the LiCs by the cooling plates. The LiC module schematic with the cooling plate is shown in Figure4.

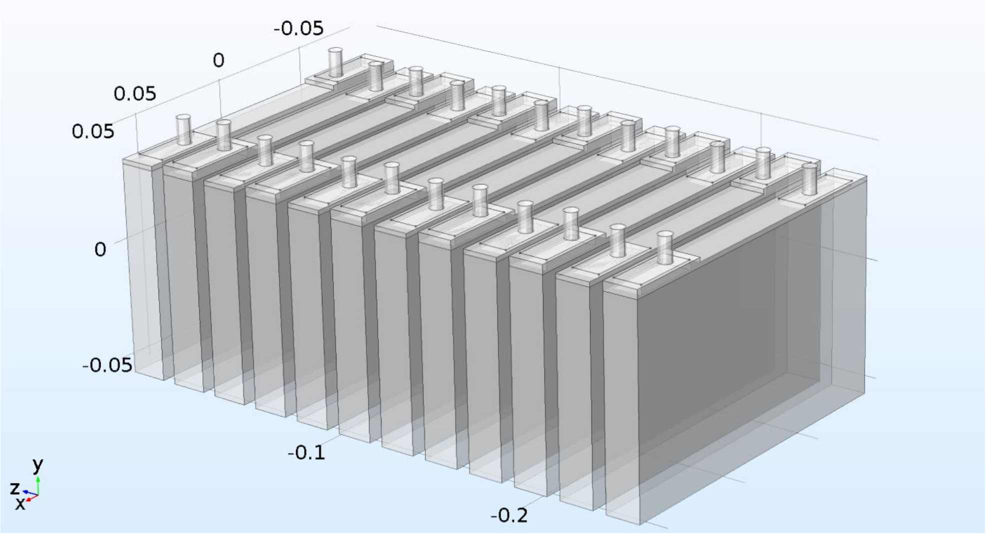


Figure3: Geometry representation of the LiC module without liquid-cooling plates.

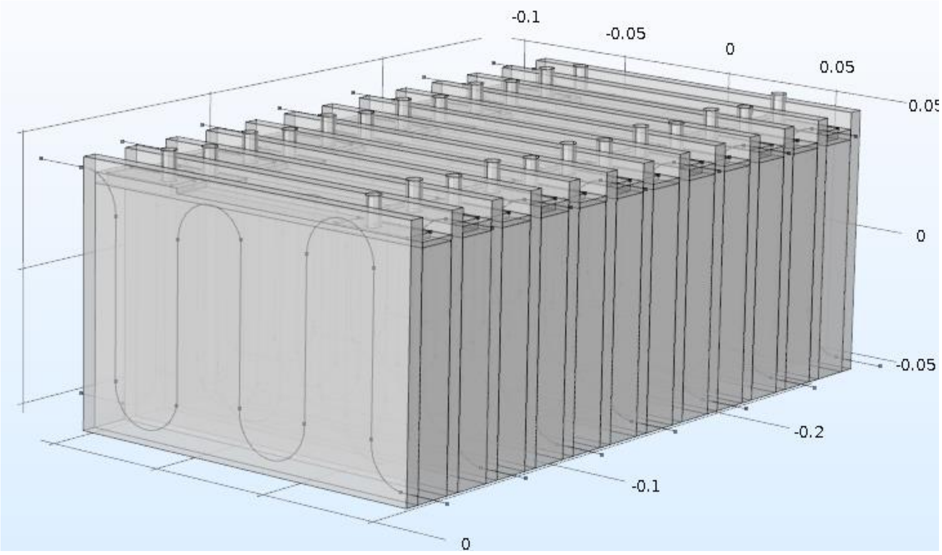


Figure4: Geometry representation of the LiC module with liquid-cooling plates.

2.4 Input parameters

As explained in the introduction, Matlab/Simulink will be used as central software with a main control and management script for steering Comsol Multiphysics. The principle of this model coupling is shown in Figure5. The heat source at the electrode domain, the current and the voltage of the LiCs are taken from the 0D-electro-thermal model developed in Matlab Simulink, and evenly distributed in the electrode and tabs computed by the 3D thermal model.

The 0D-electrothermal model coupled with a 3D lumped thermal model requires as inputs thermal parameters such as explained in section 2.3.1. The thermal parameters (conductivity (λ_x λ_y, λ_z), density (ρ), and the heat capacity (C_p) of each material domain are reported in Table1. Physical parameters or raw materials such as aluminium and copper are obtained from handbook literatures [29], [30] , while LiC thermal parameter are obtained from previous studies [28].

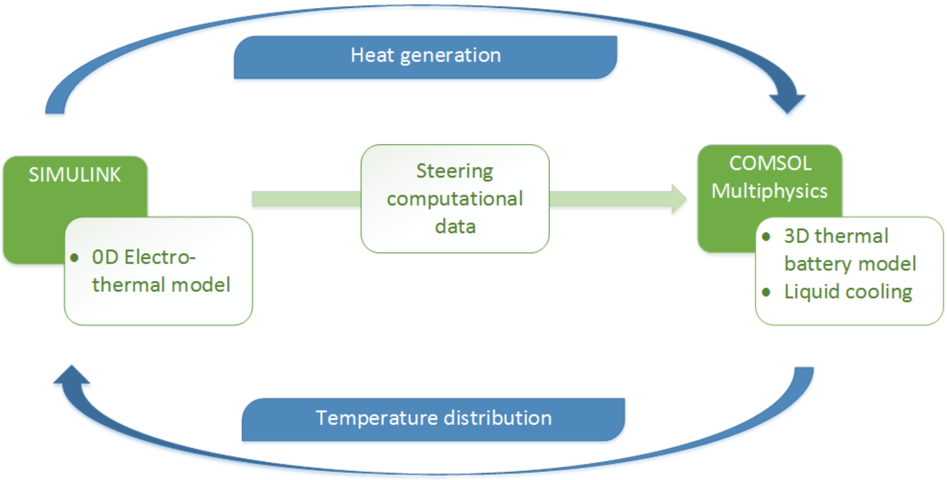


Figure5: Flowchart of the LiC module variable transfer between Simulink, Matlab and Comsol Multiphysics

Table 1: Physical parameters of the pack's components

	Density, ρ [kg/m^3]	Specific heat capacity, C_p [kg/J.K]	Electrical resistance R' (Ω)	Conductivity, λ [W/m².K]
LiC	1540	641	/	λ_x = ; λ_y = 5; λ_z
Positive tab	2700	900	9.97e-6	= 30;=
Negative tab	8960	385	5.94e-6	238
				400

3 Results and discussions

3.1 Simulation without cooling system

To evaluate the effect of the cooling plate, the temperature evolution of the sole module without cooling strategy is presented. With the different inputs (thermal parameters and applied load profile), the thermal behaviour of the LiC module has been simulated using a typical load profile for LiCs. The battery cell is cycled at 25°C between the maximum and the minimum voltages with a 30000s-power profile which goes up to 150W, as can be seen in Figure6. The initial temperature of the cell is 25°C and natural convection is considered, thus a coefficient of 5 W/m².K was set as an input.

Since the accuracy of the calculation depends heavily on the mesh and the solver, a tetrahedral mesh is used in this study. Also, the simulation was run only for 9000s which was enough to compare the thermal performances of the two strategies.

The results of the simulation are shown in Figure7 with the 3D representation at the end of the test and the 1D plot of the complete simulation. It can be seen that the module temperature increases rapidly with the power profile. Without cooling strategies the maximum temperature rises up to 44°C which could bring thermal-runaways issues in a real-life application. In addition, as seen from the 3D representation, the LiCs in the middle are naturally hotter than the external ones resulting from conduction and less surface exposed to convection. Thus, without cooling strategy, the temperature of the module appears to not be uniform leading to accelerate aging or thermal runaways in battery packs. This justifies the need for a thermal strategy while operating LiCs.

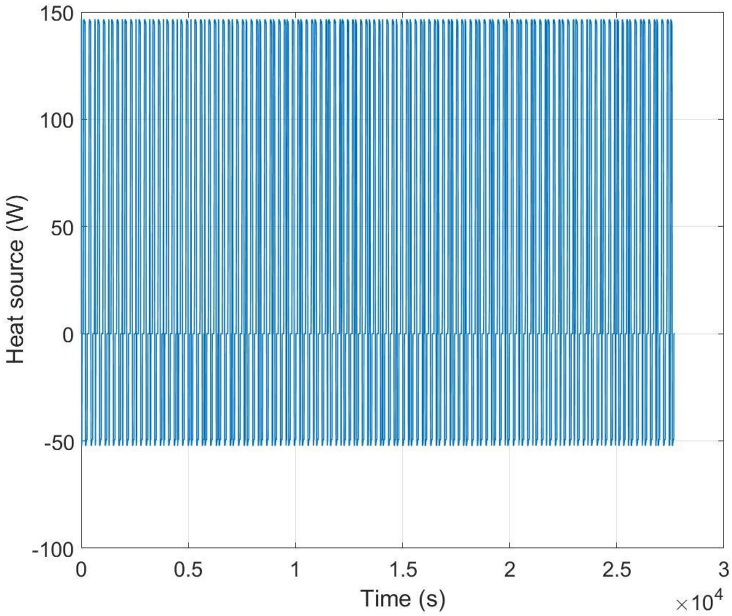
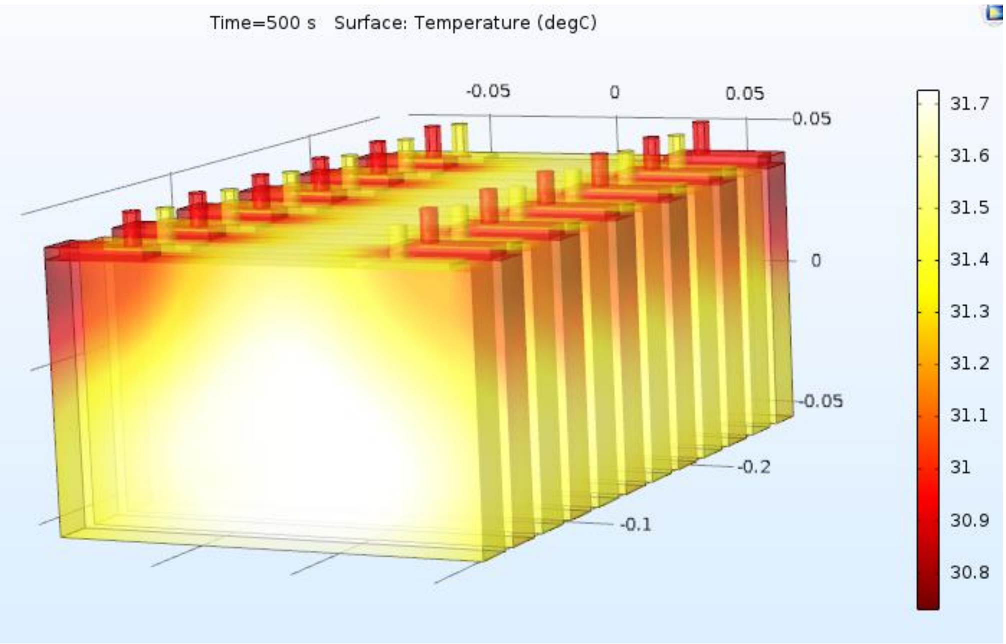


Figure 6. Applied load profile for the simulation of both liquid-cooling and without cooling-strategy.

3D thermal model for the LiC module without liquid cooling	
t = 500 s	

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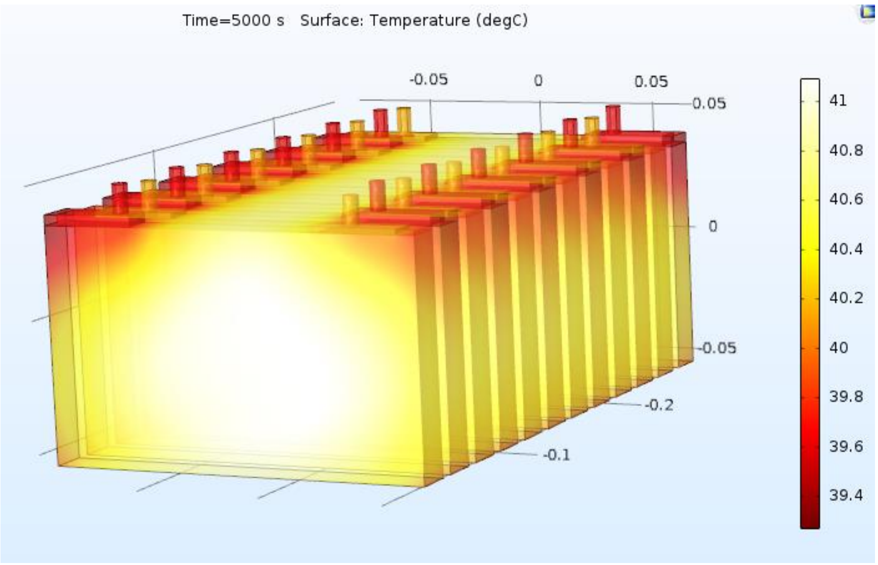
<tr><td>t = 5000 s</td><td>
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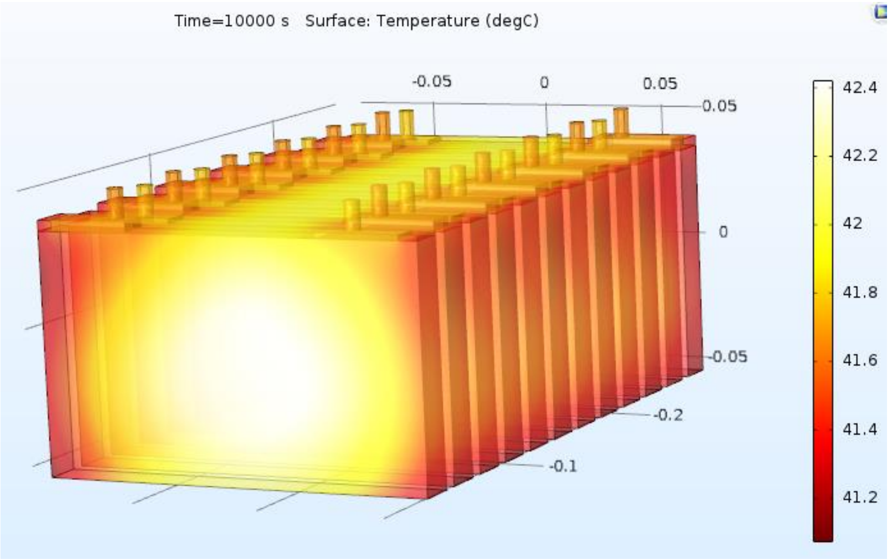
<tr><td>t = 10000 s</td><td>
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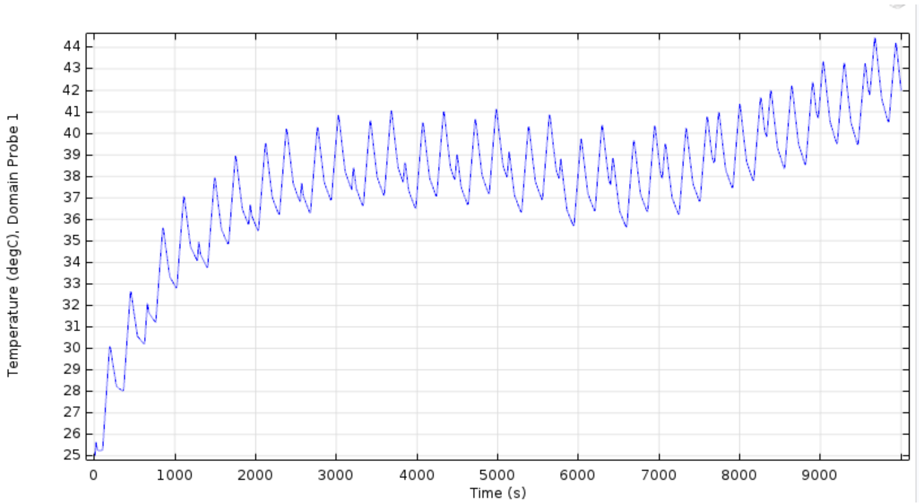
<tr><td colspan="2">Average temperature evolution of the whole battery pack.</td></tr>
<tr><td colspan="2">
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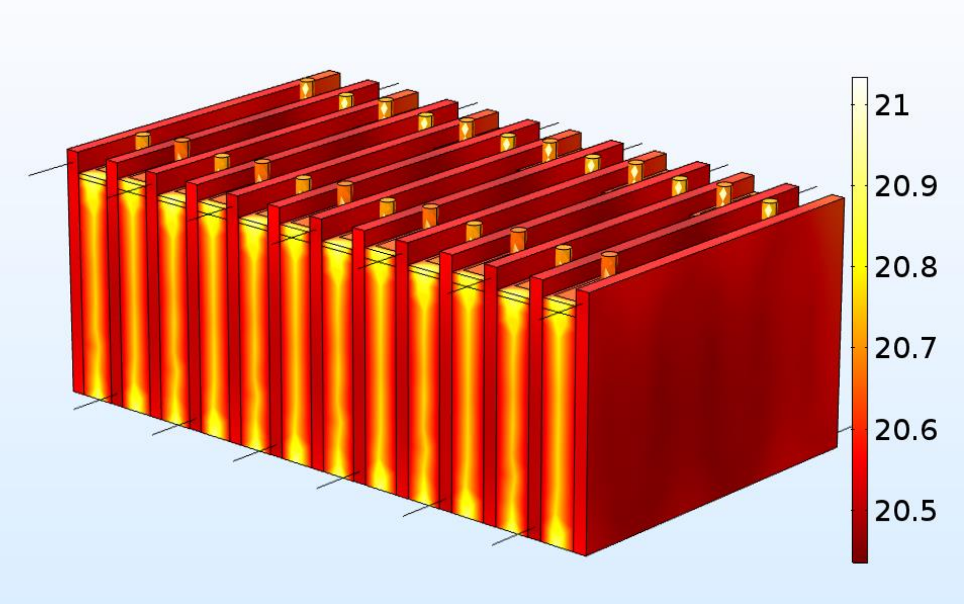
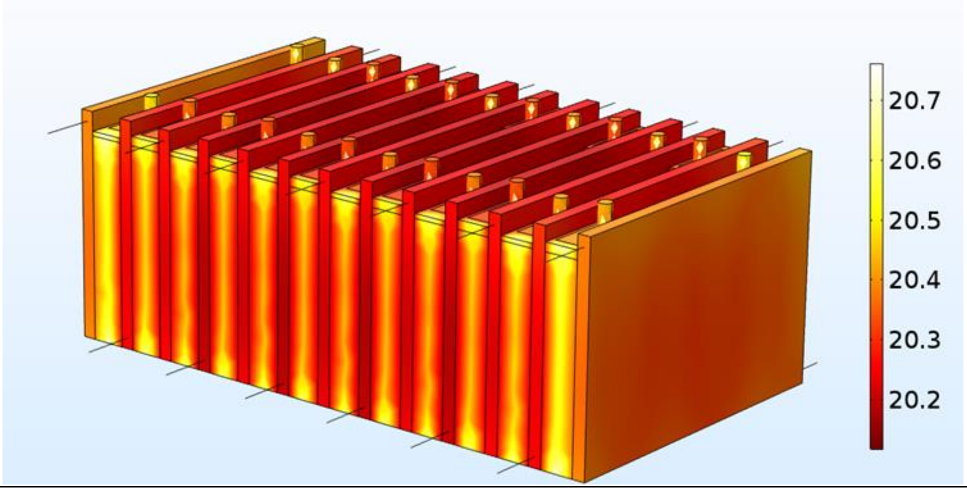
Figure 7. Simulation results for no-strategy simulation with 3D representation at the end of the profile and correspond 1D plot of the temperature.

3.2 Simulation with liquid cooling

The simulation of the cooling-plate design is performed accordingly to the same load profile shown in Figure6. The impact of the cooling plate on the LiC thermal behavior is investigated by considering the heat removed by the refrigerant and the heat dissipated through the ambient air with a convective coefficient of 5 W/m².K (natural convection. The water is used as a refrigerant with a volume flow rate of 30 l/h, which is the maximum allowable with a 5mm diameter inlet and initial temperature of 20°C. The simulation results performed for the 2300F LiC module based on a 3D thermal simulation tool in COMSOL Multiphysics are shown in Figure8 with the 3D representation and the 1D plot. It is clearly shown that the cooling plate design gives a satisfying result, the LiC module achieved a temperature uniformity and the overall temperature of the module was kept around the refrigerant temperature. The explanation can be from the conductivity of the cooling plate, where the aluminium and copper conduct rather well the temperature which transfers the heat generated by the LiCs with the temperature of the water. Ultimately, in summertime, it is clearly possible to reduce the overall temperature of the module by lowering the temperature of the refrigerant in order to keep the LiCs in an optimal temperature range. At the end, the results have clearly shown that the temperature is fully controlled and stays below 25 degrees which highly improves the performance of the module.

t = 250 s	
t = 1000 s	

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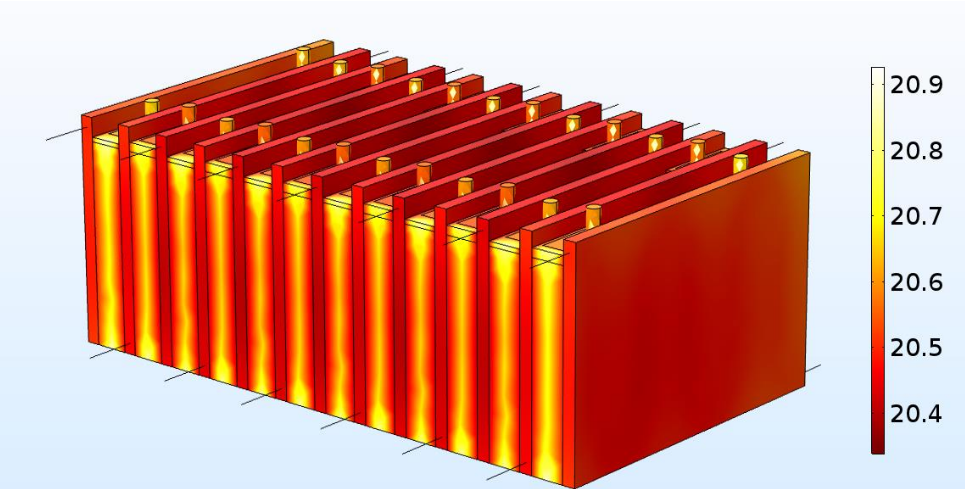
<tr><td>t = 4000 s</td><td>
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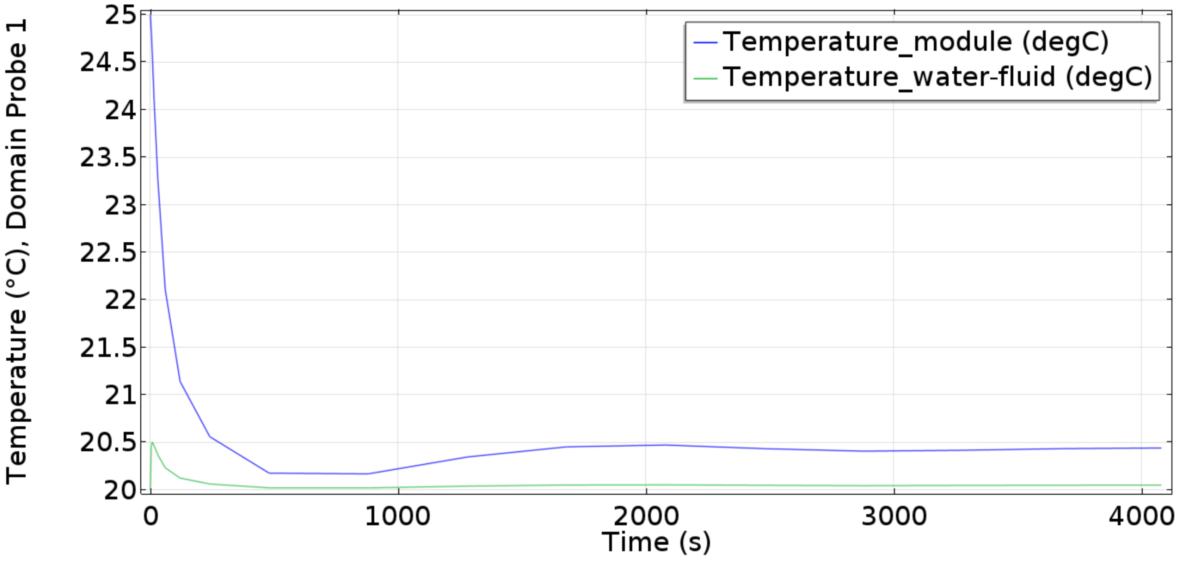
<tr><td colspan="2">Average temperature evolution of the whole battery pack.</td></tr>
<tr><td colspan="2">
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Figure 8. Simulation results for no-strategy simulation with 3D representation at the end of the profile and correspond 1D plot of the temperature.

4 Conclusions

In this study, a liquid-cooling thermal management strategy has been investigated by using a developed 0D electro-thermal model coupled with a 3D thermal model for the fluid dynamics physic. The model has been developed in two interfaces, COMSOL Multiphysics for the 3D section and Matlab for the 0D-electro-thermal model. Furthermore, the performances of a LiC module with 12 cells have been investigated under a high-current solicitation. Without liquid cooling, the temperature of the battery module increases rapidly to overreach the recommended temperature. While, with liquid cooling, it successfully controlled the maximum temperature and reduces the temperature gradient due to the high surface contact between the cooling channel and plates, which made the temperature distribution of the cells inside the pack more uniforms. Therefore, establishing a battery thermal management strategy when operating LiCs is crucial.

At the end, the model allows optimizing and sizing the thermal management of the module to enhance the module performances and lifetime. Nonetheless, other thermal management strategies could be also interesting to investigate like passive cooling with phase-change material. Before that, the validation of the LiC module for the 3D model is also a main task for future works.

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	**Prof. Dr. Joeri Van Mierlo** is a key player in the Electromobility scene. He is professor at the Vrije Universiteit Brussels, one of the top universities in this field.Prof. Dr. ir. Joeri Van Mierlo leads the MOBI – Mobility, Logistics and automotive technology research centre (http://mobi.vub.ac.be). A multidisciplinary and growing team of 70 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).