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Co-design multi-objective 3D optimization methodology for battery modules: An active air-cooling study case

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Executive Summary

To increase safety, performance and lifetime of the battery motive applications, the battery packs must be optimized to meet various application specific requirements. These are typically expressed as volumetric and gravimetric boundaries that should be optimized without compromising the energy and power capabilities as well as the thermal management of the battery cells. Battery pack design hence becomes a challenging task to achieve energy and cost-efficiency throughout vehicle's lifetime. This time consuming process that typically is addressed with trial-error and user-based experienced cannot converge to global optimal solutions while rarely exploring the whole design space. In this study, we validate a novel methodology that automatizes the battery pack thermo-mechanical design based on a three-dimensional (3D) co-design framework for Lithium-ion battery modules. Accounting an air-cooled study case, the proposed framework performs more than 250 design evaluations in relative short time for the whole available design space, ensuring the global optimal configuration of the battery module, with respect to 3 thermal and 1 mechanical constraints. As a result, the optimal battery module that is derived, is now built and experimentally tested to validate its performance with both static, pulse and dynamic loading profiles.

Keywords: battery model, automated optimization, energy storage, cooling, energy density

1 Introduction

Lithium-ion batteries (Li-ion) are being used in many electro-motive applications and energy storage due to their good operating efficiency and lifetime [1], but also as an attempt to reduce the greenhouse emissions and transit from the fossil fuel era [2, 3]. By these means, in the recent years, all types of electric vehicles incorporate an energy storage device such as the Li-ion battery cells. In order to obtain the optimal performance of the cells, they have to be monitored and controlled to stay within a safe-operating-area (SoA) [4]. The thermal safe-operating window is defined by the manufacturer according to the cell's chemistry and shape, it depends on the current rate and it is usually between 20°C to 40°C [5]. For a multi-cell topology that is required to meet the power and energy demands of an electric vehicle, a battery thermal management system (BTMS) is used to maintain all the individual cell's maximum temperature within the SoA, but also to ensure that heat is equally distributed among the cells [6, 7]. For a multi-cell topology that is required to meet the power and energy demands of an electric vehicle, a battery thermal management system (BTMS) is used to maintain all the individual cell's maximum temperature within the SoA, but also to ensure that heat is equally distributed among the cells at all ambient conditions [6, 8, 9].

Among the various approaches for the BTMS that can be found in literature, usually an air-based BTMS is implemented in electric vehicles to preserve the temperature, due to low weight and cost, good performance and scalability [10, 11]. Many studies are carried out to evaluate and optimize the air-based cooling BTMSs [12].

In [13] the optimal configuration of a battery pack composed of cylindrical Li-ion cells is proposed. Authors, showed that cell arrangement with a a small length-width ratio, in addition to inlet/outlet configuration that facilitate the air-flow over most of cells can significantly improve the cooling efficiency. Park [14], evaluated several air-cooled BTMS designs for Li-ion cells, by theoretical investigations on a proposed numerical model. Author showed that the BTMS efficiency is highly dependent on the uniform distribution of the air-passage which can be achieved by adding a tapered manifold and pressure relief ventilation to the BTMS.

Chen et al. [15], proposed a flow resistance network model to capture the friction pressure loss along the BTMS channel, which is seen as the frictions between air and channel-wall in air-based BTMS. By these means, they calculated the velocities of the cooling channels and modeled the heat transfer and temperature distribution of the battery cells. The coupling of these models showed improvements in the thermal management efficiency of the BTMS. Optimization of the air-cooled modules is also performed in [16], where authors investigated the influence of the air-inlet/outlet angles and the width of the air flow channel between battery cells. Similar assessments are performed in [17] for both a U-type and Z-type air-based BTMS where it is also concluded that the cooling efficiency and the power consumption can be improved by optimizing the aforementioned parameters. Moreover, experimental and numerical evaluations on the air-cooled BTMS is performed in [18]. Authors investigated various performance parameters, such as the channel size and the locations, the mass flow rates and the temperature influence, and they calculated the pressure drop during constant current operation. They proposed a J-type BTMS by integrating the Z- and U-type designs, and by means of surrogate modeling, they optimized the heat distribution in the battery module.

In order to estimate the optimal channel position on the air-cooled BTMSs, authors in [19] investigate several BTMS types with different input and output channels topologies, and with same design parameters such as the cell spacing, channels size and, air-flow rate and temperature. They performed a numerical study on the various designs and concluded that the cooling efficiency is improved if the channels region are both in the middle of the plenums. Li et al. [20], evaluated the effect of manifold size and mass flow rate on a U-type Li-ion module, comprised of 36 battery cells. Authors in this study, concluded that increasing the channel size of the mass flow rate can deteriorate the temperature uniformity of the cells, while an optimization is suggested to balance the air flow density and rate with the cell to cell variations and energy cost.

In our previous study, we presented the co-design framework that incorporates multi-objective particle swarm optimization algorithm [21] together with 3D electrical-thermal-mechanical analysis [22]. In this work, the optimal solution is further validated with several loading profiles showing its efficiency to a wide range of conditions. Thus, three cases are utilized to assess the applicability of the battery module at various currents, such as high demanding static current, a conventional discharge/charge cycle and at a real-driving loading profile according to worldwide harmonized light vehicle test procedure (WLTP). Once the single cell and the module models are validated, the proposed BTMS is strategically optimized to balance between the temperature management and the pressure drop, by exploring various mass flow rates, inlet/outlet channel sizes and geometrical parameters.

2 Model development

2.1 Fractional order 1D electro-thermal model

Physically meaningful battery models can be employed by means of differential equations and fractional order calculus (FOC), where the lumped capacitor of the ECM is replaced with constant phase elements (CPE), and can greatly improve the modeling accuracy [23]. De Sutter et al. [24], developed a Thevenin FOC model and achieved significant improvements on its electrical behavior compared to an empirical model. The modeling impedance was correlated to the cell's actual, by comparisons to electrochemical impedance spectroscopy (EIS) results, at various aging states of the cells. Several fractional order models (FOM) can be found in the literature, whereas the Thevenin equivalent with a current dependency on the charge transfer resistance based on the Butler-Volmer approximation (BVE) combined with a diffusion element (Warburg) [25, 26] have shown a good performance and balance between computational burden and accuracy. An R-(BVE//CPE)-W FOC coupled to a thermal model is thus proposed in this study, whereas further information on the electrical branch development can be found in our previous study [22].

2.2 Multi-physics battery pack model

The 3D thermal properties such as conductivity, cell density and specific heat are obtained from a characterization process presented in our previous work in [27], whereas the rest domain parameters are found in literature [28, 29].

The model is developed with COMSOL computational fluid dynamics (CFD) simulation tool, whereas temperature and fluid fields are solved with finite element method. A turbulent, single-phase and incompressible fluid, the mass, momentum and energy conservation are described according to the Reynolds Average Navier-Strokes equations with a k - ε turbulence model [28, 30], for the air-flow area (Eq. 1-3) and the battery cells (Eq. 4).

$$\frac{\vartheta \rho_f}{\vartheta t} + \nabla \cdot (\rho_f \bar{v}) = 0 \quad (1)$$

$$\rho_f \frac{\vartheta \bar{v}}{\vartheta t} + \rho_f (\overrightarrow{v} \cdot \nabla) \bar{v} = \nabla \bar{p} + [\nabla \cdot (\mu \nabla \bar{v}) - \phi] \quad (2)$$

$$\rho_f C_p \frac{\vartheta T_f}{\vartheta t} + (\rho_f C_p \overrightarrow{v}) \nabla T_f = \nabla \cdot \left[\left(\lambda_a + \frac{\mu_t}{\sigma_t} \right) \nabla T_f \right] \quad (3)$$

$$\rho_c C_p, c \frac{\vartheta T_c}{\vartheta t} = \nabla \cdot \left[\overrightarrow{\lambda_c} \nabla T_c \right] + \dot{Q}_{gen} + \dot{Q}_{tab} \quad (4)$$

where ρ_f represents the fluid density, $\overline{v}$ shows the average velocity, while viscosity, pressure and Reynolds stress is denoted with μ, p and ϕ respectively. Also, the time-dependent heat dissipation creates an unsteady temperature in the airfield region, described by Eq. 3. In this case, the fluid temperature is denoted as T_f, the thermal conductivity of air is λ_a and μ_t is the turbulent dynamic viscosity. The temperature equation for the battery module is described in Eq. 4, with ρ_c, C_p, c and T_c the cell's density, specific heat and surface temperature respectively, and $\overrightarrow{\lambda_c}$ the thermal conductivity at each direction.

The heat generation includes the losses generated from aluminum cell's tabs according to:

$$Q_{tab} = \frac{R' \cdot I_{batt}^2}{V l_{tab}} * N \quad (5)$$

where N is the 24 accounted tabs in a 12S1P topology. The boundary conditions for a cell are estimated between the cell's surface and the environment, according to Joule and convection phenomena. For the module level, the heat convection transfer coefficient varies during testing time and it is calculated by the software based on the air properties at the selected design (mass-flow speed, channel sizes, temperature etc). The model is solved with COMSOL software using MUMPS solver, with a default physics-controlled unstructured tetrahedral mesh, and non-slip boundary conditions being imposed to the walls and initial temperature set at the ambient temperature i.e 25°C.

2.3 Coupled 1D and 3D battery model

The proposed FOM 1D electro-thermal model derives the heat losses of the cell over time, which are fed to the 3D model to further evaluate the temperature gradients in a module level. Figure 1, shows the coupled 1D electro-thermal model.

3 Co-design thermo-mechanical 3D optimization framework

The 1D model feeds the heat generation rates to the 3D model and the thermal management of the module can be evaluated, according to the structure parameters and the fluid controls. The methodology not only investigates the optimal parameters for a single battery modules, but it accounts various inlets and outlets. Hence, the optimal thermal design is selected considering various criteria (maximum cell temperature, maximum cell surface variation, cell-to-cell uniformity, overall volume required to achieve low temperature) for various solutions [22].

Fig. 2, shows the design configuration of the proposed air-cooled BTMS.
In sub-figure (a), it is shown the inlet/outlet orientation and size, which in this study is denoted as L_{cha} and it equals approximately to a third over the total channel's area, denoted as L_{mod}. With blue and orange colors, the inlet and outlet channels are respectively represented. In sub-figure (b), the top view of the BTMS is shown, with the BTMS total length and width dimensions are denoted as x_1 and x_2,

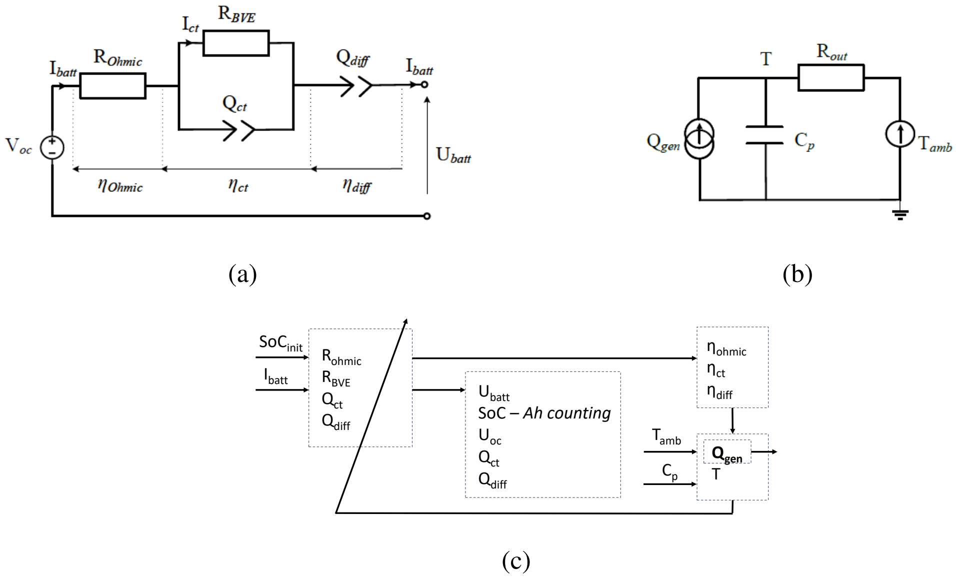

Figure 1: (a) Electrical FOC model (b) Thermal branch (c) Coupling the electrical FOC with the thermal 1D model.

respectively, while x_3 represents the space from the cells to the BTMS's side wall. In sub-figure (c), the proposed Z-type parallel-flow BTMS is shown with the air inlet and outlet channels, whereas sub-figure (d), shows the internal configuration of the cells with respect to the BTMS boundaries, as x_4 the height of the BTMS, x_5 and x_6 the distances between the outer cells to the x- and y-axis side walls, respectively, and x_7 the cell to cell distance. Lastly, it should be noted that symmetries for all sides are considered. The proposed dimensions for the implementation of the BTMS are gathered in Table 1.

Table 1: Mechanical parameters of the proposed air-based BTMS.

Main parameter	Implemented value	Unit
x_1	201.2	$[mm]$
x_2	412.9	$[mm]$
x_3	26.6	$[mm]$
x_4	152.6	$[mm]$
x_5	20	$[mm]$
x_6	30.8	$[mm]$
x_7	3.9	$[mm]$

Performance of the optimal solution is shown in Fig. 3, with a comparison between the natural convection (right sub-figure) and proposed thermal solution (left figure), at the $1200sec$ of the 2C discharge, and with the least required volume.
This solutions is further build and validated in this work. A Z-type BTMS is proposed in this study with parallel air-flow to the cells.

4 Experimental test-bench

For the 12S1P module implementation, an electrical characterization of more than 100 cells is performed to select the ones with closest values in the Ragone plot, in terms of capacity and impedance. A variation up to 3% and 11% respectively is exhibited at the beginning of life (BoL) and at the same testing conditions.
The hardware setup for the testing includes a climate chamber to preserve the cell's surface temperature close to the various environmental conditions. The single-cells are connected to a PEC ACT0550 tester, capable of up to DC 5 V measurements, whereas the module is connected to a PEC SBT8050, capable

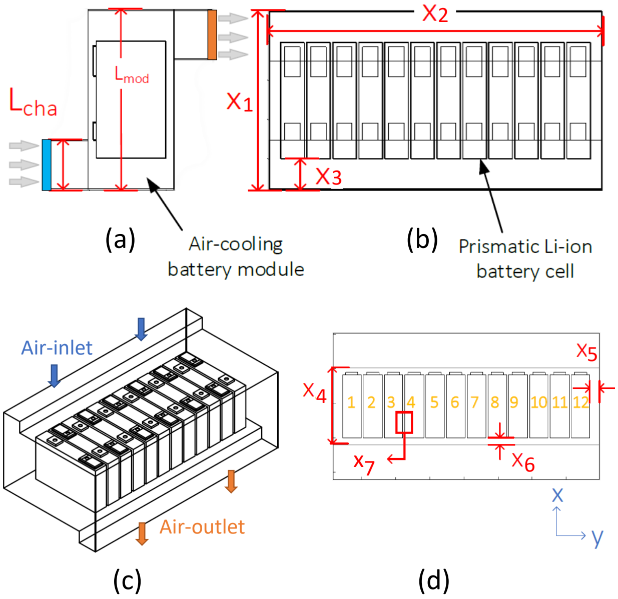

Figure 2: (a) Side view (b) Top view (c) Proposed BTMS inlet/outlet channels (d) BTMS cells configuration

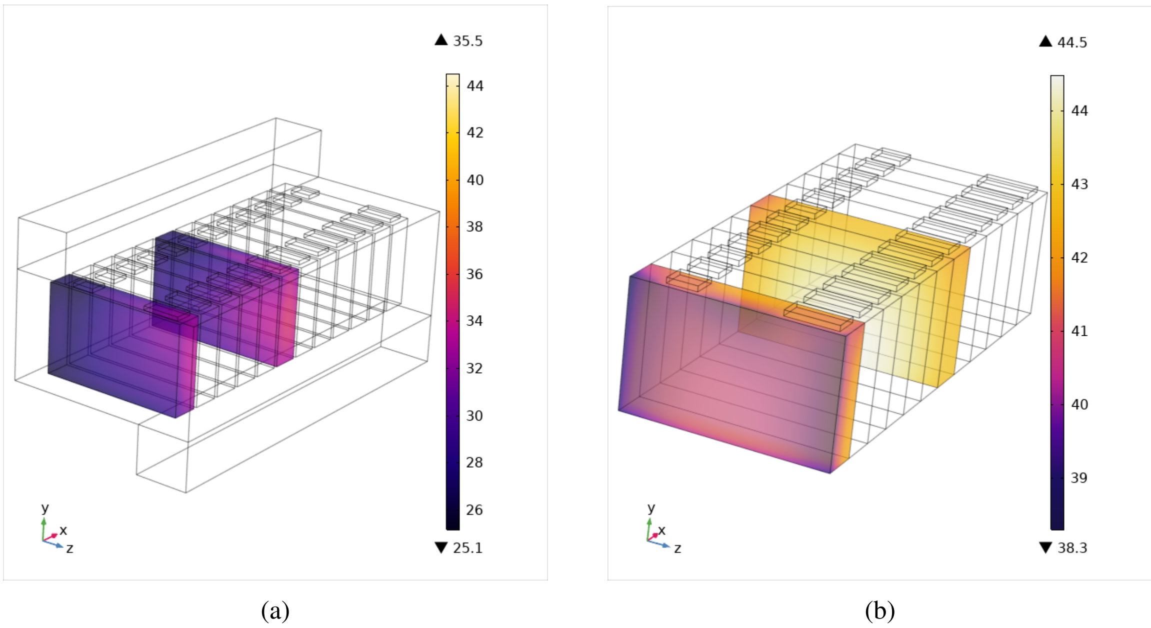

Figure 3: (a) Proposed BTMS from [22] and (b) Natural convection heat distribution.

of up to 80 V DC, and both with a $\pm 0.005\%$ voltage accuracy. The module is connected to pre-charge circuit and a fuses-relays safety box, and it is monitored by a commercially available battery management system (BMS). Anemometer and temperature data logger are used to measure the mass flow rates and obtain the cell's surface temperature in the module. The overall test-bench is shown in Fig. 4, with green and blue path indicating the cell and module level testing, respectively.

5 Results

The BTMS evaluations are performed at 25°C ambient temperature, for a constant current discharge with 2C-rate, a discharge/charge cycle at the recommended rates (1C), and a dynamic loading profile

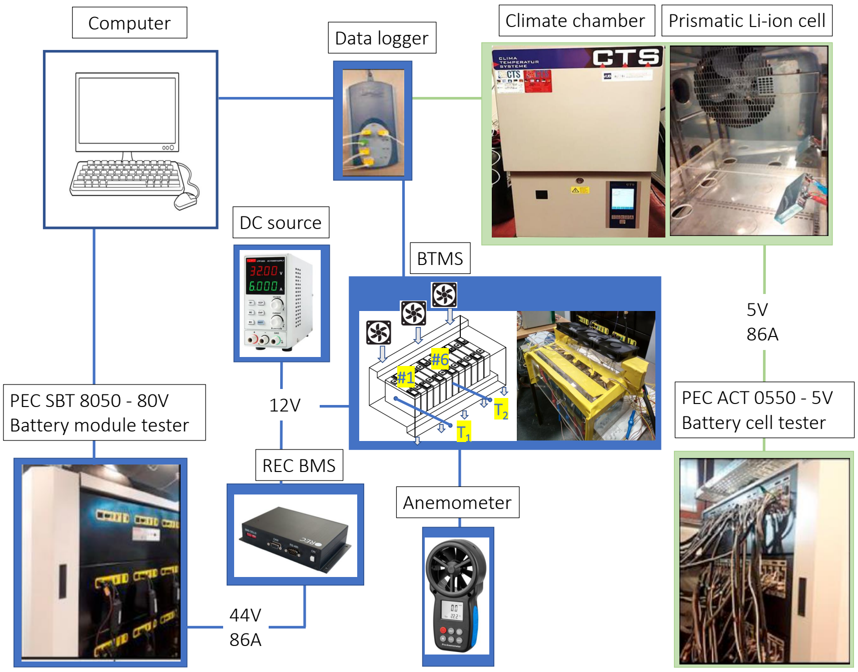

Figure 4: Experimental setup during the cell (green) and module level (blue) characterization and validation.

(WLTC).

5.1 Constant current profile at 2C

The results will be shown at the full paper's version The module is validated for a static current with an initial SoC at approximately 85%, discharged up to the 20% SoC. Fig. 5 shows the experimental and numerical results at the locations of T_1 (first cell) and T_2 (sixth cell). For comparison reasons, the blue line shows the behavior of a natural convention model (NC BTMS) without an applied cooling solution.

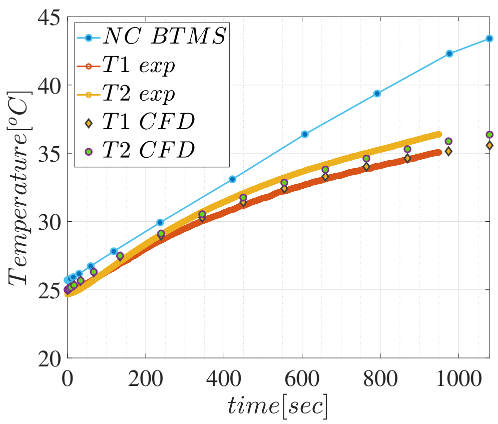

Figure 5: Constant current BTMS validation.

It is observed that the proposed BTMS model fit with good agreement the experimental data and can keep the maximum temperature lower than 36°C, which is approximately 9°C lower than the NC-BTMS.

5.2 Pulse current profile at 1C

The time dependent heat generation is supplied to the CFD model. Even though for the two current pulses the test time is higher and the heat generation is based on impedance data from both charge and discharge profiles, the temperature behavior can be tracked with high accuracy, as shown in Fig. 6.

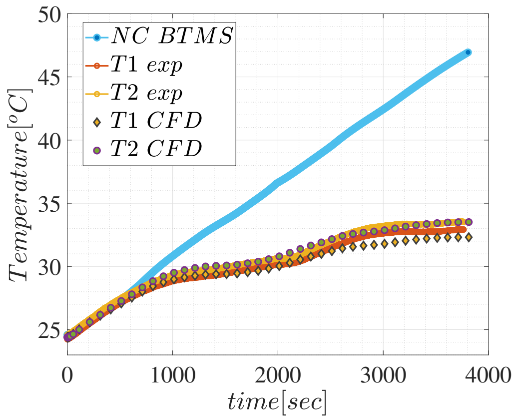

Figure 6: Discharge-Charge current BTMS validation.

Also, the proposed module is capable of keeping the maximum temperature below 35°C compared to the NC-BTMS, while the heat uniformity is established with thermocouples T_1 and T_2, and the good agreement between experimental and CFD values.

5.3 Dynamic profile WLTC

5.3.1 Cell-level WLTC evaluation

The R-(BVE//CPE) branch is very efficient for fast dynamics that are mainly accounted in this profile. Throughout the whole test, the relative error is not exceeding 0.5% of the actual voltage value, as shown in Fig. 7.

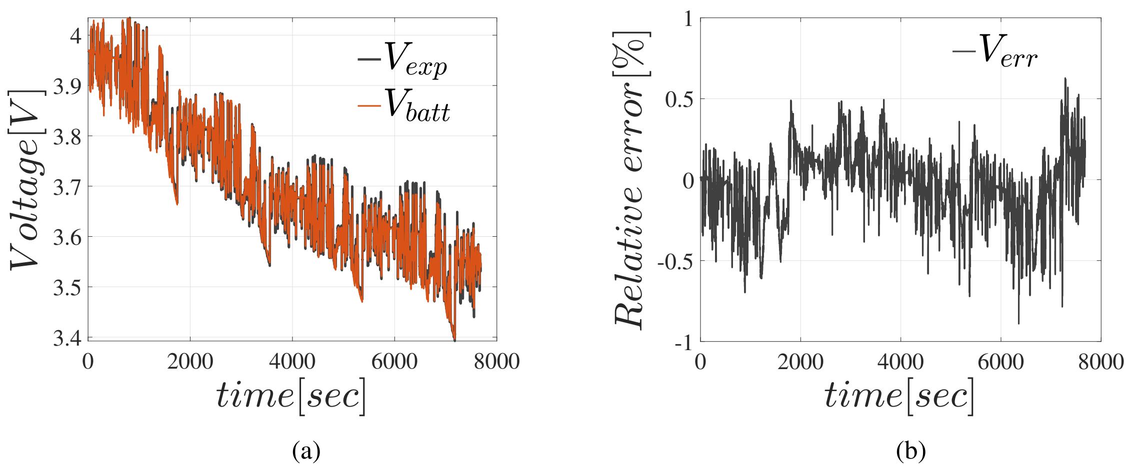

Figure 7: (a) Dynamic profile single cell voltage behavior (b) Relative error.

Hereafter, the proposed electro-thermal model captures the temperature behavior with high accuracy, with the corresponding heat generation shown in Fig. 8.

5.3.2 Module level WLTC validation

The dynamic profile is applied to the 12S1P air-based module and the experiment data against the CFD are shown in Fig. 9.

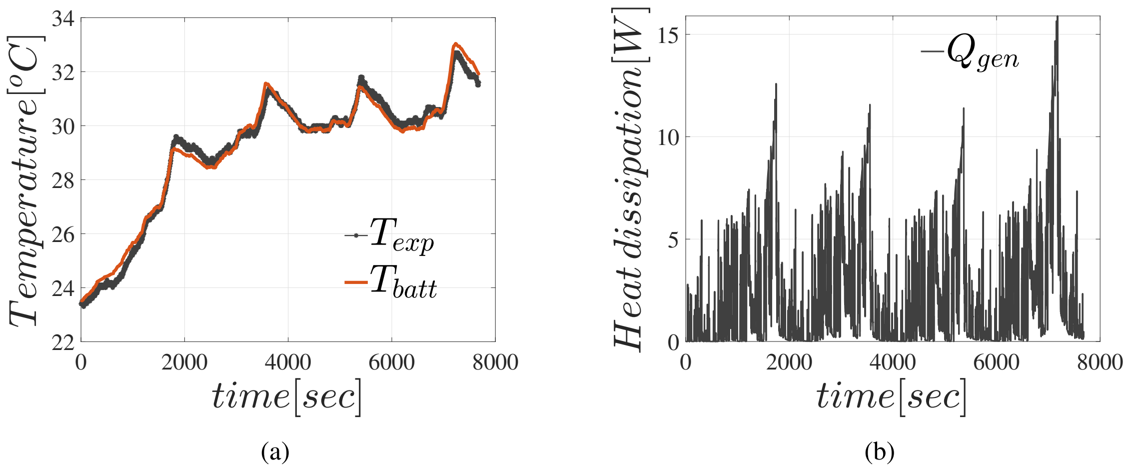

Figure 8: (a) Single cell temperature behavior (b) Heat generation.

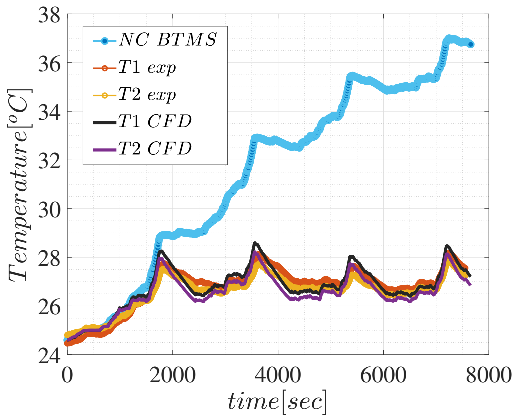

Figure 9: Dynamic current BTMS validation.

A good agreement is achieved both on maximum temperature and heat distribution for the proposed module. It is observed that the consecutive current cycles can elevate the maximum temperature at the end of experiment (aprx. 20% SoC) to 38°C. Based on the NC-BTMS model indicated with the blue line, the temperature has an increasing rate of change which can lead to surpass the safety window if no cooling solution is applied. However, the proposed BTMS shows a stable thermal trend, without exceeding 28°C.

6 Conclusions

In this work the performance of an air-cooled battery thermal management system (BTMS) is studied for a battery module composed of 12 high energy prismatic Li-ion cells connected in series.
A physical-meaningful electrical model is built based on fractional order calculus which maps with high accuracy the impedance of the cells. The single cell electrical model is coupled to a thermal branch and it is evaluated with three different current profiles, a maximum static discharge current, a discharge-charge cycle and a consecutive dynamic profile. A good agreement between the modeling and the experimental values is achieved, underlined with the low relative errors obtained in each study case. Hence, the heat generation is derived and supplied to an efficient three-dimensional model, that it is also validated against experimental results at the various current profiles. The roles of natural convection (NC BTMS) and forced convection are studied separately for the proposed BTMS, under the intense static and dynamic loads.
By optimizing the key performance parameters such as the mass flow velocity and the channel size, one can conclude that their increment leads to a maximum temperature reduce. Also, the cell to cell distance increase has a reverse impact on the temperature and the pressure drop. By these means, the thermal

management of the proposed architecture is enhanced while the pressure drop is kept at minimum range. Forthcoming work includes the study on the proposed BTMS applied to a more representative battery pack, which will consider the overall cost based on the weight, volume and similar key parameters from a real-life scenario.

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Presenter Biography

Dr. Theodoros Kalogiannis obtained his diploma degree in Electrical Computer Engineering and Energy Technology and his MSc degree in Wind Power Systems from DUTH and AAU respectively. He holds a PhD degree in the field of energy storage entitled as "Physical Optimization of Lithium-ion Battery Modules" obtained in VUB- Battery Innovation Centre, where he is currently working as a Post-Doctoral Senior Researcher. His expertise expands from lifetime testing and characterizing commercial battery cells, to design optimization of mechanical, thermal and electrical architectures of multi-cell topologies for various applications on the battery energy storage such as electric vehicles and grid support.