Electrothermal Battery Pack Model for Automotive Application: Design and Validation

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Abstract
Thermal modeling of the battery is an effective way to understand how the design and operating variables affect the battery thermal response during its operation. This paper presents a method for modeling the electrical and thermal behavior of a Lithium-ion battery cell. First, the model takes into account both the reversible entropic heat generation and the irreversible resistive heat to predict the temperature of the battery. Then, the single-cell model will be extended in order to validate the module or battery pack behavior. To this end, a coupled CFD and thermal analysis on a module is proposed and experimentally validated.

Keywords

Thermal Management System (TMS), lithium-ion battery, battery model, Electric-Thermal model, electric vehicles, temperature analysis, automotive applications, Computational fluid dynamics (CFD), thermal control

I. INTRODUCTION

Automotive manufacturers are developing and deploying vehicles with an increasing level of electric hybridization, from hybrid electric vehicles (HEVs) [1] to plug-in hybrid electric vehicles (PHEV)[2], [3] and eventually to pure electric vehicles (EVs). By virtue of high gravimetric and volumetric energy densities along with long cycle life and no memory effect, Lithium-ion batteries are being intensively studied and used as power sources for automotive applications [4]. However, one of the defects of this technology is a particular behavior in difficult environmental situations. In fact, Li-ion battery performance is highly sensitive to the operational temperature [5]. In particular, the Li-ion batteries suffer severe power loss under temperatures below zero degrees Celsius, and present high risk of thermal runaway at extremely high temperatures, over 50 degrees Celsius[6], [7].

For this reason, a thermal management system is necessarily required to control the system temperature within a permitted range and maintain the temperature uniformity throughout the overall system. At this scope, a thermal model is needed to fully understand the thermal characteristic of Li-ion batteries and predict their thermal behavior under different operations and environmental conditions [8].

In literature, there are many battery models. For some applications, a simple electric model can be sufficient, [9]–[11] in other cases there are more complex electrochemical models [12] that are highly accurate [13], but hard to be fully parameterized and with large computational capacity [14]. For Automotive application, it is necessary the best trade-off between accuracy and simplicity, for this reason, Equivalent circuit models are commonly used for control-oriented applications and are suitable for BMS implementation [15].

However, the thermal models are more complex. They are generally based on the resolution of energy conservation equations to provide the temperature distribution inside the battery [16].

This paper aims to validate a single Matlab-Simulink model that describes both the electrical and thermal behavior starting from the characterization of the single element up to extend its validity at the module and pack level.

At this scope, though the commercial software Comsol Multiphysics, a coupled CFD and thermal analysis on a module made up of 9 cells is proposed and experimentally validated. Then, the accuracy of the proposed Matlab-Simulink model will be assessed by comparing its results with those obtained from the Comsol model.

The remainder of the paper is organized as follows. In the next section, an overview of the single-cell Matlab-Simulink model is presented, then the computational fluid dynamic problem, developed in Comsol Multiphysics, will be explained. In the third section, the description of the experimental setup occurs. A discussion of the experimental results used to validate the model is then put forward. Finally, in the last section, the conclusion and future perspectives will be presented.

II. NUMERICAL MODEL

A. *Matlab-Simulink Model*

Li-ion batteries are complex systems due to their high dynamic and non-linear behavior. Battery modeling requires a deep investigation into both electrical and thermal parameters that affect battery performances. For these reasons, a coupled electrical and thermal battery model able to provide real-time battery parameters during discharge operation for BMS integration in automotive application is proposed. For the electrical analysis, a double polarization Thevénin equivalent circuit model is used due to its high effectiveness and low complexity. It is made up of a voltage source to represent the voltage of the cell in thermochemical equilibrium condition, a series resistance that accounts for the internal resistance of the cell, and two resistance-capacitance blocks to model the fast and slow dynamic inside the cell caused by the electrochemical reactions. The model is based on a previous experimental electrical characterization that provides the values for the Thevénin circuit parameters as a function of state of charge and temperature. The thermal problem consists in the resolution of the energy conservation equation inside the cell, which is considered as a solid, homogeneous, and anisotropic medium in which only conductive heat transfer occurs. Moreover, due to the axisymmetric condition, the heat transfer occurs only in the radial and axial coordinates. Finally, the thermophysical properties of the cell are considered constant and temperature independent. According to the previous assumption, the governing equation of the problem is:

$$\rho c_p \frac{\partial T}{\partial t} = k_r \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + k_z \left(\frac{\partial^2 T}{\partial z^2}\right) + q \qquad (1)$$

where: ρ is the battery density, c_p is the specific heat capacity, k_r is the thermal conductivity in the radial direction, and k_z is the thermal conductivity in the axial direction. The heat generation rate is the sum of two components, an irreversible term to take into account the heat generated inside the cell due to the Joule's effect, and a second reversible term caused by the entropic variation of the electrochemical reaction:

$$q = I(V_{ov} - V) - IT\frac{\partial V_{ov}}{\partial T} \qquad (2)$$

The finite differences numerical discretization algorithm with an initial value and set of boundary conditions must be imposed to solve the thermal problem described by the equation (1). In particular, at time zero the cell is at ambient temperature and for the whole transient problem, null heat transfer occurs along the axial direction due to the axisymmetric condition, whereas conductive heat transfer is imposed to be equal to the air convective one at the external surfaces.

The proposed model is developed in Matlab-Simulink environment and it's the combination of the aforementioned electrical and thermal models. It simulates the discharging phase of a Li-ion battery evaluating for the whole transient process the values of the Thevénin electrical circuit parameters as a function of state of charge and temperature. Moreover, the model is able to estimate the internal heat generation rate and the temperature evolution across the cell.

B. Comsol Multiphysics Model

The aim of the work is to validate the results obtained from the proposed single-cell model and to extend its validity to a larger module. At this scope, a proper simulation is set through the commercial software Comsol Multiphysics. The analysis of the airflow field inside the elementary unit and the thermal field in both fluid and solid domains is performed to evaluate the transient thermal response of the elementary unit when it is cooled downy by medium. Moreover, the mutual heat transfer among cells,

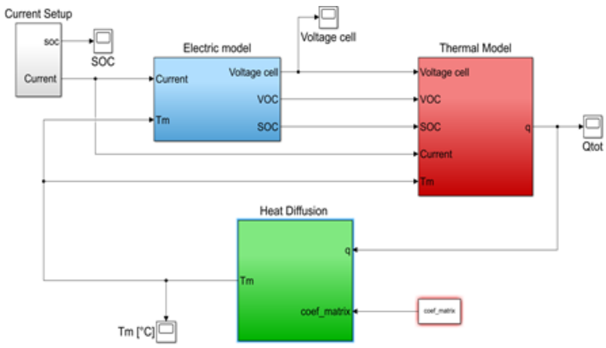

Fig. 1 Matlab-Simulink Eletrothermal model

and the presence of possible thermal hot spots are studied. Finally, the evaluation of the cooling power absorbed by the air and rejected out of the unit is evaluated in order to establish the effectiveness of the air-based thermal management system. The battery module contains nine cylindrical Li-ion cells which are mechanically held by a lower and upper support. The cells are arranged with an inline configuration in the direction of airflow and are characterized by the transversal and longitudinal pitch equal to 3 mm to guarantee a good circulation of the airflow. The cells are discharged separately at 1 C-rate and are cooled down with a constant airflow. Li-ion cells technical specifications are provided in Table 1.

Table 1 LG battery characteristics

Property	Value
Nominal capacity	3.0 Ah
Nominal voltage	3.6 V
Max. voltage	4.2 V
Min. voltage	2.5 V
Max. discharge current	20 A
Max. charge current	4 A
Operating temperature	-20 °C to +75 °C
Cycle life	300 cycles

The cells are considered as isotropic and homogeneous medium with temperature-independent thermophysical properties to simplify the computational cost of the analysis and due to the difficulties of the measurements involved. A conjugate heat transfer problem is set, in which air fluid flow is considered to be laminar and incompressible, whereas the convective and conductive heat transfer occurs in the fluid and solid domains, respectively. The governing equations of the problem are the continuity equation and the momentum and energy conservation laws. For the fluid problems:

$$\rho\nabla\cdot(u)=0 \qquad (3)$$

$$\rho(u\cdot\nabla)u=\nabla\cdot[-pI+\mu(\nabla u+(\nabla u)^{T})]+F \qquad (4)$$

$$\rho c_p\frac{\partial T}{\partial t}+\rho c_p u\cdot\nabla T+\nabla\cdot(-k\nabla T)=0 \qquad (5)$$

where: ρ is the air density, u is the velocity vector, p is the pressure, μ is the dynamic viscosity, F is the body force. vector, c_p is the air specific heat capacity and k is the air thermal conductivity.

For the solid domain only the energy conservation equation occurs:

$$\rho c_p\frac{\partial T}{\partial t}+\nabla\cdot(-k\nabla T)=Q \qquad (6)$$

where: ρ is the cell density, c_p is the cell specific heat capacity, k is the cell thermal conductivity and Q is the heat source.

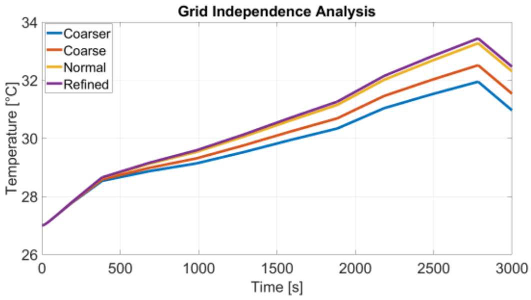

Fig. 2 Matlab-Simulink Eletrothermal model

The air velocity at the inlet surfaces is fixed to 1 m/s and no-slip boundary conditions are applied at the contact surfaces between fluid and solids. A uniform temperature equal to 27 °C is set as the initial condition for the thermal problem, and the internal heat generation rate evaluated by the Matlab-Simulink problem is used as the input value for the simulation. Finally, the outflow condition with both null relative pressure and the heat transfer rate is set at the outlet section.

The battery module was modeled to different mesh sizes to check for the grid independence analysis. The study was repeated according to four different mesh sizes, in particular, a coarser mesh with 62377 tetrahedral nodes, a coarse mesh with 91669 nodes, a normal mesh with 180142 nodes, and a refined mesh with 719355 nodes were used. The temperature evolution of the central cell was used as a parameter for the mesh sensitivity analysis. As can be seen from the figure (2), the solution is grid-independent after a refinement procedure, thus the normal mesh is used to avoid the long computational cost requested by the refined one.

III. EXPERIMENTAL SETUP

The aim of the experiment is to validate the model developed in Comsol Multiphysics environment; in particular, the evolution of the cell surface temperature during the discharging phase is evaluated and compared with the temperature profile provided by the numerical simulation. A multichannel battery tester is used to discharge separately the nine cells with a suitable current equal to the nominal capacity of the cells. The battery tester has 16 channels in parallel and it can provide a current up to 20 A in a voltage range of 0-5 V. The figure (3) represents the battery tester used for the experiment.


Fig. 3 Battery Testesr

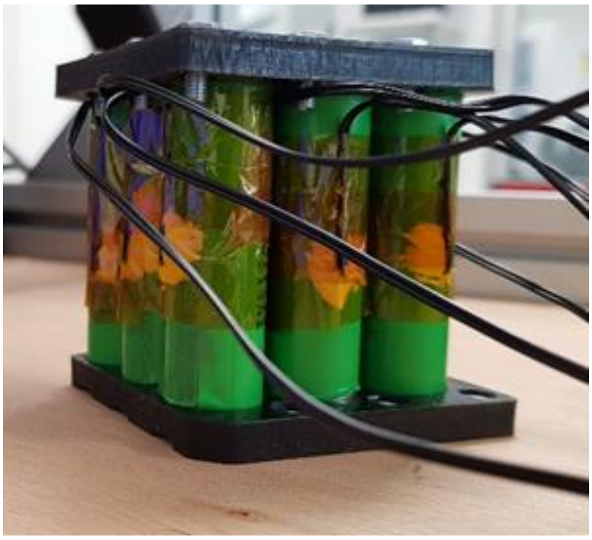

Fig. 4 Device under test - Elementary module

In the first stage two battery holders were designed to keep the cell in the proper position. The holders are made in rapid prototyping thanks to a 3D printing machine. The average temperature of each cell is monitored through a NTC10000 thermistor, which is fixed at the mid-height of the cell through a thermal paste used to enhance the thermal conductivity between the sensor and the cell.

The electrical connection between the cells and the cables of the battery tester is guaranteed by means of small aluminum plates which are bolt to the holder at one side and welded to the cell positive and negative poles at the other side. The plates welding is performed with a resistance spot welding machine provided by Amada Miyachi

A fan is used to reproduce the operative condition of a battery cell cooled by an air-based thermal management system. The fan provides a constant airflow according to the supply voltage. Moreover, the system under investigation is placed inside a box to simulate the operative conditions typical of a wind tunnel experimental simulation. The box used to control the cell surrounding environment is characterized by an inlet section that provides the fresh air and an outlet section in which is placed the fun. The inlet air velocity provided by the fun is measured through a dynamic pressure anemometer with Pitot tube TROTEC TA400. The length, width, and height of the box are 810 mm, 550 mm, and 630 mm, respectively. The elementary unit is immersed in the fluid; thus, it is placed at the center of the box. The experimental workbench is shown in figure (5).

Fig. 5 Experimental workbench

IV. Numerical Procedure and Validation

In this section, the validation workflow is presented. Starting from the electrical characterization of the cell, the parameters of the Thevenin electrical equivalent circuit model was found. A deeper analysis of the proposed characterization procedure can be found in previous work. These values represent the input parameters to use in the model developed in Matlab-Simulink environment, which is able to evaluate the internal heat generation rate of a cell during a discharging process. Successively, the thermal source term obtained from the model is used as an input for the Comsol Multiphysics CFD simulation. The simulation results are validated by comparing them with the temperature evolution of the nine cells measured experimentally in the wind tunnel. Then, the temperature evolution obtained with the Matlab-Simulink model is validated with respect to the temperature evolution of the central cell in the elementary unit of the Comsol simulation.

V. Results

The constant current battery module discharge phase at 1C was simulated. The heat generation rate during the whole transient process was provided by the Matlab-Simulink model. The flow field in the fluid domain was solved through a CFD analysis, whereas the thermal field in both fluid and solid domains was calculated through a finite element method simulation. First, the Comsol simulation results are provided in terms of the flow field and thermal field. Then, the cell temperature measurements during the experimental discharging phase at 1C are presented. Finally, a comparison between the temperature obtained from the experiment and those obtained from the simulations occurs, to validate the proposed model.

A. *Flow field*

Forced circulation is used to enhance heat dissipation from the cells. In the next two figures, the flow field in the flow direction and transversal to flow direction are provided, respectively. The air inlet velocity in the simulation is set equal to 1 m/s from the experimental measurement. A boundary layer occurs near the cells due to the no-slip boundary condition, thus the velocity is zero at the contact interface between cells and fluid. The figure shows how the velocity reaches its maximum value at the spacing between the cells. Behind the battery cells, there are separation zones, where stagnation point, air recirculation, and backflows occur. Moreover, the flow field is symmetrical in the transversal direction due to the cell inline arrangement.

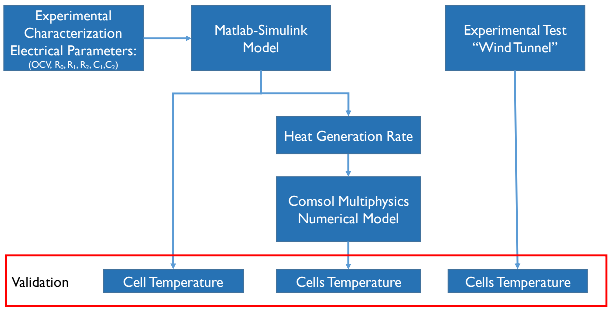

Fig. 6 Matlab-Simulink Eletrothermal model

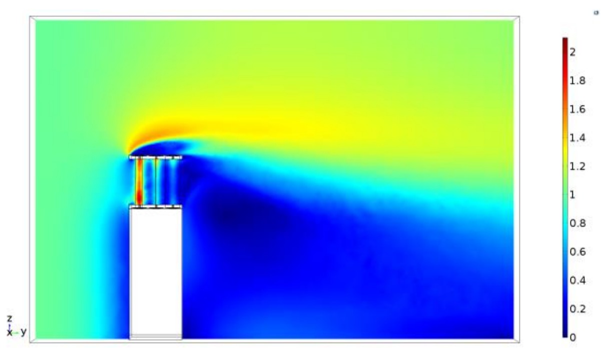

Fig. 7 Matlab-Simulink Eletrothermal model

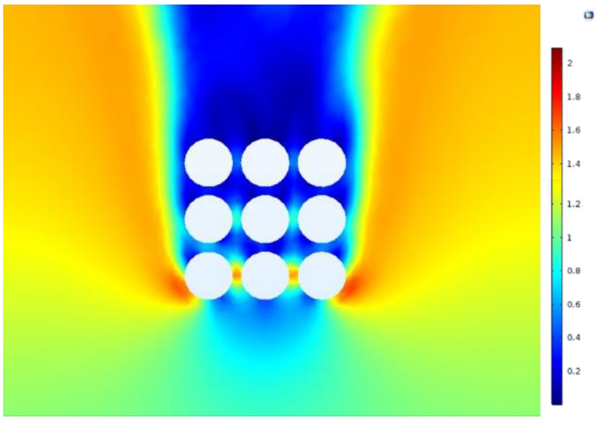

Fig. 8 Matlab-Simulink Eletrothermal model

B. Temperature field

During the discharging process, a temperature field occurs inside the cell due to the internal heat generation rate linked to Joule's effect and electrochemical reactions. The initial temperature of the whole system is characterized by thermal equilibrium between the cells and the external fluid.

The temperature field is strictly linked to the flow field, indeed, the higher the flow velocity, the higher the heat transfer rate, and the lower the temperature. As a consequence, an increase of the fluid temperature occurs in the direction of the flow: the fresh air absorbs the heat released from the first cell and becomes warmer, thus, when it reaches the last cells, a lower thermal gradient between cell and fluid occurs and the heat transfer becomes ineffective. A thermal gradient higher than 5 °C occurs inside the module, as it can be seen in the figure (X). The poor temperature uniformity inside the module under investigation demonstrates how the air-based thermal management system represents an ineffective cooling solution for large battery pack. From the graph of the cell's temperature evolution obtained from the Comsol simulation it can be seen how the cells increase monotonically their temperature during the whole transient process. Moreover, a negligible thermal gradient occurs among cells in the transversal direction, whereas there is a large temperature difference between cells at the inlet and outlet sections. Finally, the cell in the central position has a quite high temperature with respect to the other cells on its side, due to the mutual heat transfer with the surrounding cells.

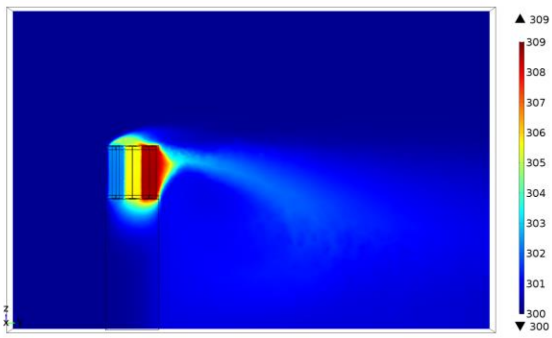

Fig. 9 Matlab-Simulink Eletrothermal model

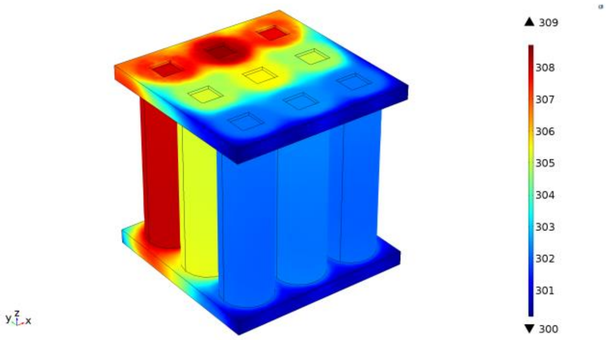

Fig. 10 Matlab-Simulink Eletrothermal model

C. Numerical-experimental correlation

The aim of the work is to validate experimentally the cell temperature evolution provided by the Matlab-simulink model. At this scope, the temperatures of the nine cells obtained from the numerical simulation in Comsol are compared with the temperature measured during the experiment and represented in figure (X). In particular, to validate the result of the numerical simulation the central cell temperature evolution was considered. From the figure (X), it can be seen how the two curves have a quite similar trend: a steep temperature increase occurs in the first part of the discharging process, then there is a linear temperature increment followed by another non-linear term. The temperature curve has a high non-linear behavior which is typical for Li-ion cell with a high state of charge and depth of discharge. The relative error between experimental and numerical temperatures is shown in figure (X). It reaches a maximum value equal to 8.6% which can be considered acceptable due to the complexity of the simulation.

The numerical results are compared with the average temperature evolution of the cell obtained from the Matlab-Simulink model. A circular optimized procedure is used, firstly the Matlab-Simulink model provides the internal heat generation rate to be used in Comsol simulations. In the CFD elementary unit simulation, the convective heat transfer coefficient is extracted from Newton's cooling law and it is used in a second run of the Matlab-Simulink model. In particular:

$$h=\frac{-k\left(\frac{\partial T}{\partial x}\right)\Big|_{x=wall}}{(T_W-T_\infty)} \quad (1)$$

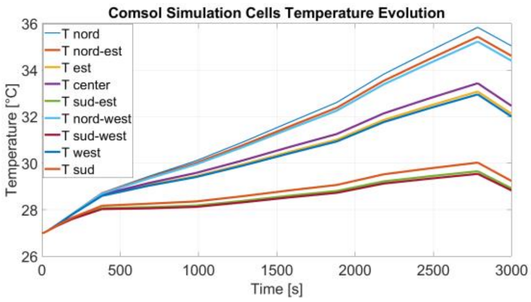

Fig. 11 Matlab-Simulink Eletrothermal model

where: k is the thermal conductivity of the fluid, T_W is the surface temperature of the cell and T_∞ is the bulk air temperature.

In figure (X) the relative error of the central cell temperature evolution obtained by the Simulink model and measured experimentally is presented. The maximum relative error is 5.3% which can be considered acceptable due to the lightness of the Simulink model.

VI. Conclusions

In this study, a light and accurate model developed in Matlab-Simulink environment is presented and experimentally validated. The model is able to simulate the discharging phase of a li-ion battery from both an electrical and thermal point of view. In particular, the cell voltage response, the internal heat generation rate, and the cell temperature evolution during the whole transient process is provided. The model requires as input the parameters of the Thevenin equivalent circuit model which are obtained from a preliminary electrical characterization procedure. Moreover, a coupled CFD and thermal simulation is carried out upon an elementary module made of nine cells to evaluate the mutual heat transfer and the scalability of the proposed Simulink single-cell model to a large battery module. The following conclusions can be drawn:

- A thermal gradient higher than 5 °C occurs inside the battery module, due to the different cooling conditions of the cells at the inlet and outlet sections.
- The air-based thermal management system can not guarantee temperature uniformity across the module; thus, it does not represent a suitable cooling solution for a large battery pack.
- During the discharging process at 1C, the cell under investigation shows a temperature increase equal to approximately 7 °C.
- An error equal to 8.6% occurs between the central cell temperature evolution obtained from the CFD simulation and the experimental measurement.

- An error equal to 5.3% occurs between the temperature evolution obtained from the single-cell Matlab-Simulink model and the central cell temperature evolution obtained from the experimental measurement.

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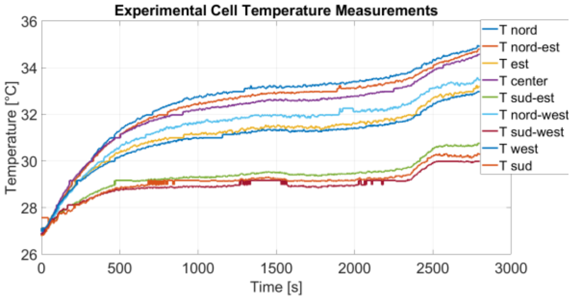

Fig. 12 Matlab-Simulink Eletrothermal model

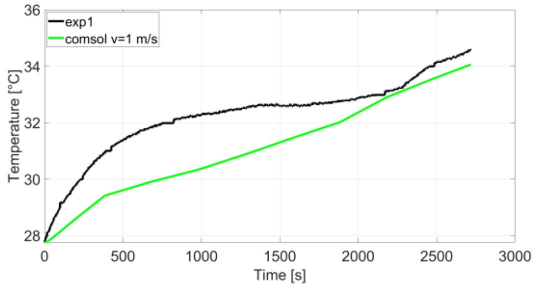

Fig. 13 Matlab-Simulink Eletrothermal model

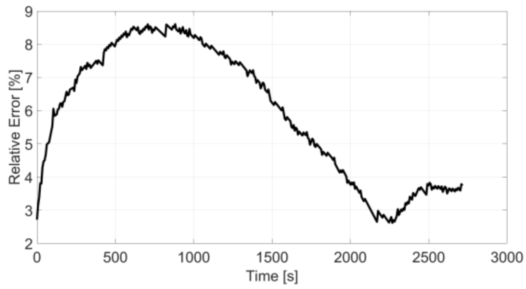

Fig. 14 Matlab-Simulink Eletrothermal model

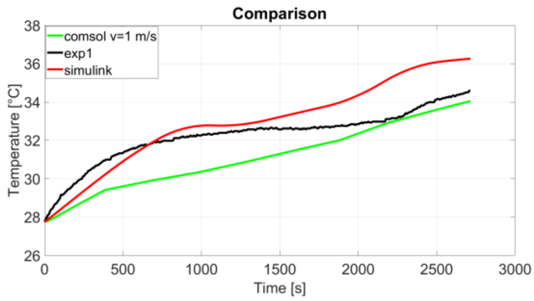

Fig. 15 Matlab-Simulink Eletrothermal model

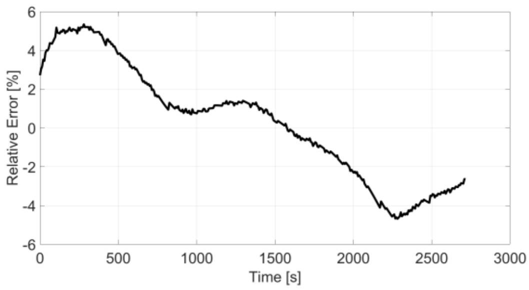

Fig. 16 Matlab-Simulink Eletrothermal model

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