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# EXPERIMENTAL AND NUMERICAL STUDIES OF SELECTED TYPES OF BATTERIES – STATE-OF-THE-ART

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### *Abstract*

*The purpose of this article is to provide—on the basis of the literature review—the current state of knowledge concerning the experimental and numerical studies of selected types of batteries. The authors focused their actions on batteries that could to be the base for an energy storage system possible to apply in hybrid shunting locomotive. Following standards, e.g. IEEE 1625, IEEE 1725, UL 1973 and UL 2271 were taken into consideration within the context of the experimental research. Numerical analysis based mostly on the original solutions proposed by research teams. In recent times, the significant growth of interest in hybrid vehicles can be observed. Therefore, appropriate design of the energy storage system for each case is necessary. Moreover, the battery working process in hybrid vehicles is very specific, hence determination of their working conditions depending on the vehicle application is required. Very often, the experimental studies related with the batteries are based on the parameters recorded during the test conducted during the regular operation of the vehicle. Furthermore, research teams also carry out numerical analysis based on e.g. the finite element method (FEM). Such analyses can be focused on the thermal analyses of single cell or cells, analyses of the electrochemical effects as well as a coupled electro-thermal analyses.*

***Keywords:*** *battery, cell, experimental studies, numerical studies*

## 1. Introduction

In recent times, the significant growth of interest in hybrid vehicles can be observed. Development of such vehicle entails many problems. An appropriate design of the energy storage system is the most notable of the these problems. Specificity of work of the energy storage system and the batteries themselves depends largely on the purposes of the vehicle use. Designer has to remember that not every type of battery can be used in hybrid vehicles. There are several types of batteries e.g. lead-acid batteries, nickel-cadmium batteries, nickel-metal hydride batteries, lithium-ion batteries and each of them has its pros and cons. therefore, it is necessary to determine the operating conditions for the batteries and perform appropriate laboratory tests and/or computer simulations to verify whether the selected battery type can be applied. Moreover, the typical batteries usually have a certain operating temperature, which retains their parameters, and the appropriate cooling system has to be designed to ensure the correct battery operation.

## 2. Experimental tests of the batteries

Experimental tests depend on the type of considered batteries. For the nickel-cadmium batteries general recommendation is to conduct the tests for the already formed batteries and no older than four months. Moreover, the batteries have not been previously tested. The tests should be carried out in a temperature of 20°C ± 5°C and they include e.g. checking the electrical capacitance and the electrical capacitance at low temperatures, and checking the charge conservation.

Lead-acid batteries are constructed of the lead electrode, the lead oxide ($PbO_2$) electrode and 37% of aqueous solution of sulphuric acid used as the electrolyte. The capacity test is supposed to be performed for such batteries. It is recommended that the test cycle duration corresponds to the duration of the battery operation cycle. Most assumed cycle duration varies between 5 and 8 hours, whereas the final discharge voltage is equal to 1.75–1.80 Volts [1].

Another considered type of batteries is the lithium-ion ones. Nowadays, it is the most popular type available on the market. The lithium-ion batteries are used in small electronic devices (mobile phones, tablets) and hybrid vehicles as well. Based on the available literature it can be observed that they are also the most commonly used type of battery for hybrid railway vehicles [2]; e.g. shunting locomotives like Toshiba HD300, TEM9H Sinara Hybrid, Railpower Green Goat GG20B. Such popularity of this type of energy storage causes that there are many standards specifying the procedures of their research. The most popular is the IEEE 1625 standard *Rechargeable Batteries for Multi-Cell Mobile Computing Devices* and the IEEE 1725 standard *Rechargeable Batteries for Cellular Phones*. There are also standards for the use of lithium-ion batteries in vehicles and trains: e.g. Underwriters Laboratories Standards UL 1973 *Batteries for Use in Light Electric Rail Applications and Stationary Applications* and UL 2271 Batteries for Use in Light Electric Vehicle Applications [3].

## 3. Numerical analysis of the batteries

Based on the available literature, numerical analysis of batteries and accumulators can be divided divide into following groups:

- thermal analysis of the cell/cells,
- analysis of the electrochemical effects,
- thermal-electric analysis of the battery.

A special attention has been focused on NiMH batteries especially for those applied in hybrid vehicles. In case of NiMH batteries, it is important to know the temperature they achieve during their operation in selected circumstances. In order to determine this temperature the thermal analysis can be carried out using e.g. finite element method FEM.

An example of the FEM thermal analysis of a single cell of the NiMH battery is described in [4]. The whole procedure for the simulations is depicted in Fig. 1. A fully charged battery ($SOC_0 = 100\%$) at a known temperature $T_0$ gives the initial conditions for the simulation. The known charge-and/or discharge cycle for the battery current $I_B$ is discretized in time. For each time step, the actual $SOC$ is computed. Therewith the up to date battery voltage $U_B$ is computed applying the previously prescribed conditions ($SOC$ and $T$). A proper $U_B$ allows the computation of the FEM-based current flow field. Hereafter the power losses $P_{loss}$ can be computed. Finally, the thermal FEM-procedure will be applied to obtain the up to date temperature $T$ and the next time step computation can be treated [4].

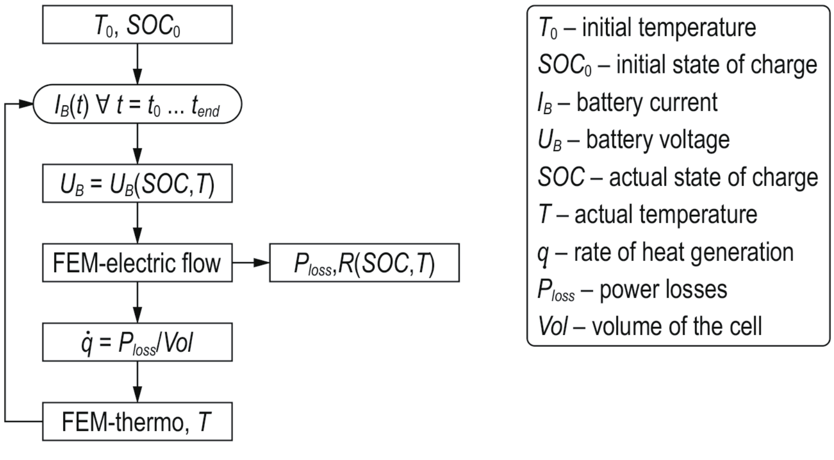

*Fig. 1. Scheme of the calculation procedure used in thermal analysis described in [4]*

An example of a similar analysis has been also presented in [5]. The author considered a pack of lithium-ion batteries. The FEM model was generated using the COMSOL Multiphysics simulation software. The simulation model includes ten cells, an air domain, a cover and the Battery Management System (BMS), Fig. 2.

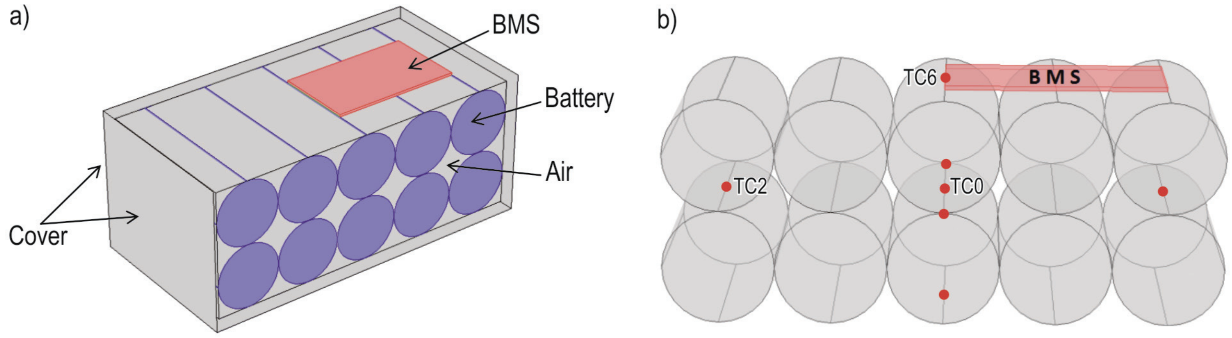

*Fig. 2. Geometry of the FEM model of the pack of lithium-ion batteries used in analysis (a) and location of thermocouples used in validation experimental tests (b) [5]*

In the next step, the author defined the thermal properties for each component in the model, e.g. the overall thermal conductivity $k$, the average cell heat capacity $C_p$, and the average cell density $\rho$. The thermal parameters have been determined from earlier experimental studies. The thermal conductivity of the Li-ion cell was assumed anisotropic since in the axial direction the layers of cell are in series, whereas in the radial direction – in parallel. The battery cells domains were selected as a heat source, which describes heat generation within the domain. The heat source was specified as total heat per volume in the domain. The Battery Management System (BMS) was another heat source specified with a simplified heat generation model included. The author took into consideration three different meshes for the enclosure and the cells – fine, normal and coarse. Temperature grid presented in Fig. 3 is an example of the obtained results [5]. The author compared FEM results with the ones obtained during the experimental validation test. Fig. 4. shows time-histories for both cases for selected measurement points – thermocouples TC0, TC2 and TC6 only (see Fig. 2).

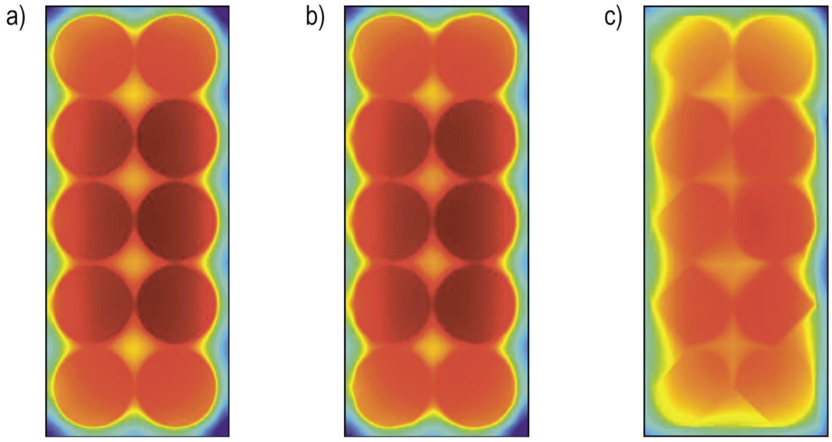

*Fig. 3. Temperature grid for different meshes of the enclosure and the cells – fine (a), normal (b) and coarse (c) [5]*

Thermal parameters of the cylindrical Sony-18650 battery with a capacity of 1.5 Ah was analysed in [6]. The battery FE model includes following components: anode, anode current collector (copper), separator, cathode, cathode current collector (aluminium) – Fig. 5a. The battery was analyzed for the initial temperature of 300 K (26.8°C) and the thermal conductivity on a wall of the battery equal to 7.17 W/(m·K).

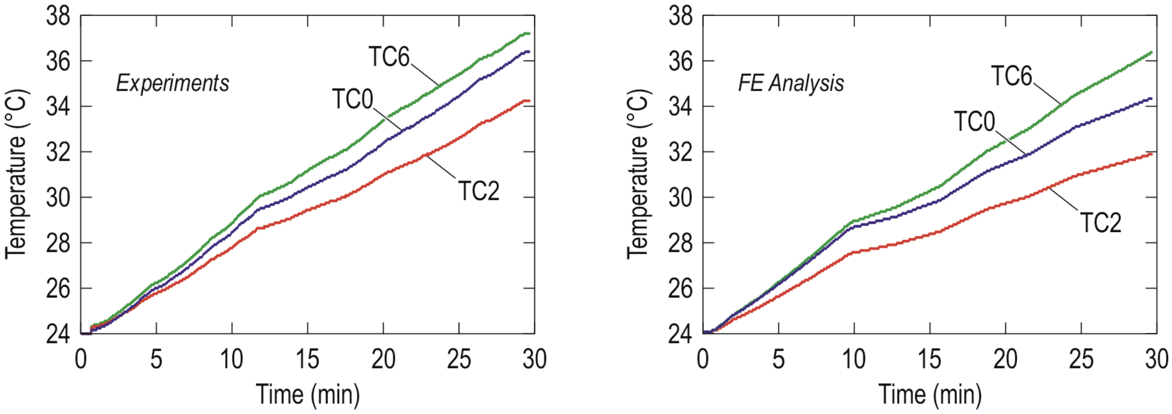

*Fig. 4. Comparison of the time-histories of the temperature in different locations of the battery pack [5]*

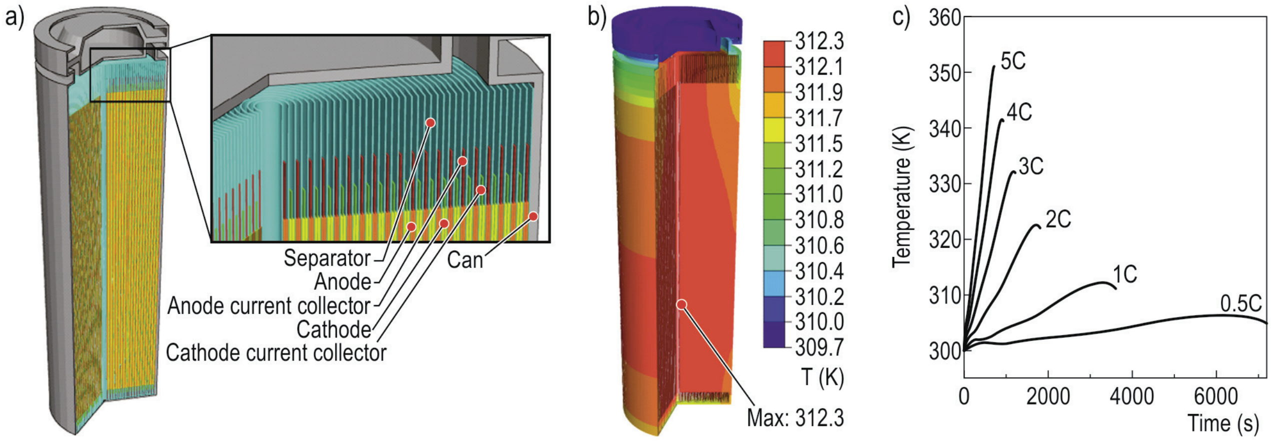

*Fig. 5. Scheme of the cylindrical Sony-18650 lithium-ion battery (a), temperature distribution at a discharge rate of 1C and SOC = 0.1 (b) and temperature time histories for different discharge rates (c) [6]*

Thermal analysis was carried out using ABAQUS finite element analysis (FEA) solver. The 4-node structural and quadratic element plane with axisymmetric option was applied in FE model. The heat sources at components (anode, cathode and both current collectors) were taken into account. Analyses allow obtaining the temperature distribution contours during the discharge cycle of the battery as well as the temperature time-histories for different discharge rates (Fig. 5c) [6].

Electro-thermal simulation describes the interaction between electrical and thermal components. Both of these elements are mutually dependent since the current flow generates heat and – on the other side – the temperature affects the performance of the entire system [7]. Finite element method can be used to carry out such simulation. The thermal model can be directly transformed into a model of the electrical circuit. The classic equation of the finite element method can be written as:

$$E\dot{T} + KT = F\,, \tag{1}$$

where $T$ is a vector of the unknown voltages, $E$ is the capacity matrix and $K$ is the resistance matrix.

Equation (1) is not compatible with system level simulation because of its large dimensionality. Therefore, the model order reduction (MOOR) is necessary. An example of the method for reducing the degree of the model is presented in [8]. The authors start from the following equation:

$$E\dot{x} + Kx = f\,, \tag{2}$$

where $E$ is the heat capacity matrix, $K$ is the heat conductivity matrix, and the state vector $x$ contains the degrees of freedom – for thermal problems the nodes' temperatures. The load vector $f(t)$ is divided in constant vectors $b_i$ and in time functions $u(t)$. Constant vectors transfer the time functions to specific degrees of freedom [8]:

$$f(t) = \sum b_i \, u(t)\,. \tag{3}$$

Afterwards, the $x$ vector is replaced by the $y$ vector, wherein:

$$y = C\,x\,, \tag{4}$$

where $C$ is the output matrix.

The idea of MOR is to reduce the dimension of the state vector $x$ and preserve the dynamical behaviour of the input/output relation (Fig. 6). Several different techniques for model reduction were developed and some of them use the so-called projection idea [8]:

$$x = V\,z + \varepsilon\,. \tag{5}$$

The projection matrix $V$ approximates the state vector with a few of degrees of freedom $z$. $\varepsilon$ is the approximation error. The reduced order model is found by projecting (2) into the lower subspace as follow:

$$V^T E\,V\,\dot{z} + V^T K\,V\,z = V^T B\,V\,u\,, \tag{6}$$

$$y = C\,V\,z\,. \tag{7}$$

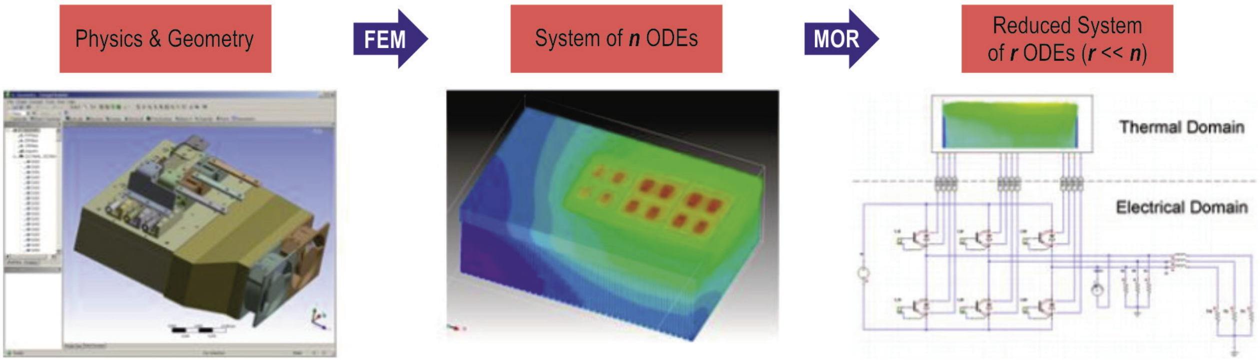

Fig. 6. The idea of MOR applied in electro-thermal simulation (ODE – ordinary differential equation) [7]

An example of electro-thermal simulation of the battery pack FE model is presented in [7]. The model includes 33 individual batteries and cooling system (Fig. 7). The system model is coupled with an electrical battery cell model in Simplorer software that allows reducing the matrices from the originally developed full files. Proposed approach [7] allows the authors to evaluate the effect of discharge current.

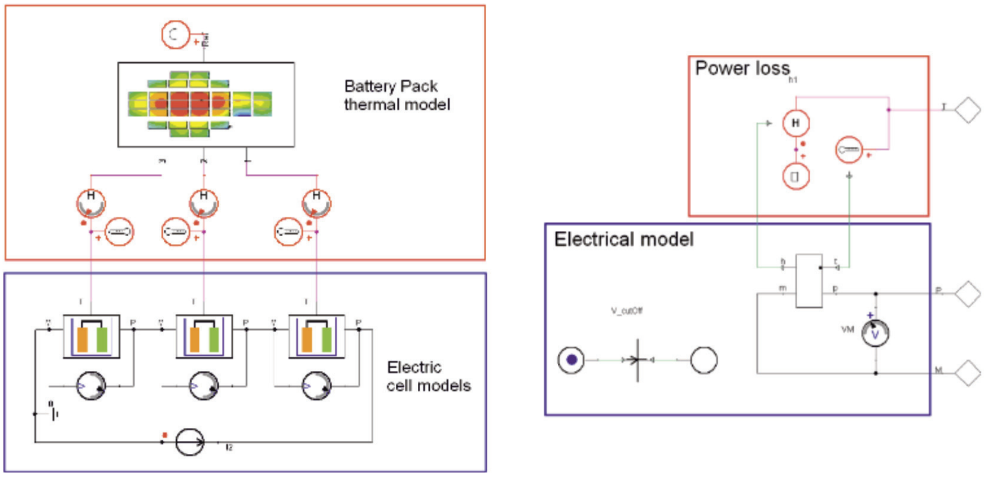

Fig. 7. Electro-thermal battery coupling in Simplorer software [7]

An example of electrochemical process analysis was presented in [9]. Two-dimensional model of electrochemical processes occurring in the lithium-ion battery was developed. Fig. 8a shows a simplified scheme of proposed model. The authors used several different methods in order to solve the system of equations due to high level of complexity. FE method was applied to discretize the problem in the spatial variables (Fig. 8b). After that, the Backward Euler method was used for the time discretization. The obtained system on nonlinear equations was linearizing with the Newton method. Finally, for the linear system the ILUT preconditioned BiCGSTAB (Bi-Conjugate Gradient STABilized) method was used [9]. Appropriate boundary conditions – Dirichlet and Neumann – were applied on the anode, cathode and electrolyte edges and interfaces. Initial conditions were limited to the initial concentration of lithium ions $c_0$ (mol/cm$^3$) in all three components and the initial potential $\Phi_0$ (V) for the anode and cathode only. Conducted test gave information about the concentration of lithium ions and potential distribution. Several results are depicted in the form of contours in Fig. 9.

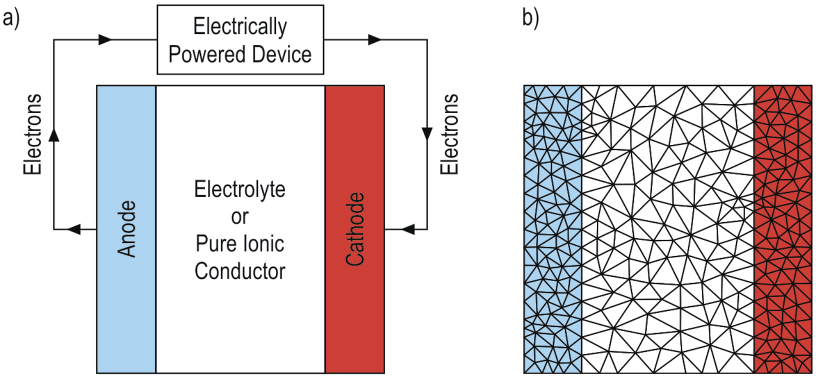

*Fig. 8. Li-ion battery scheme (a) and its FE model (b) used in analysis of the electrochemical process [9]*

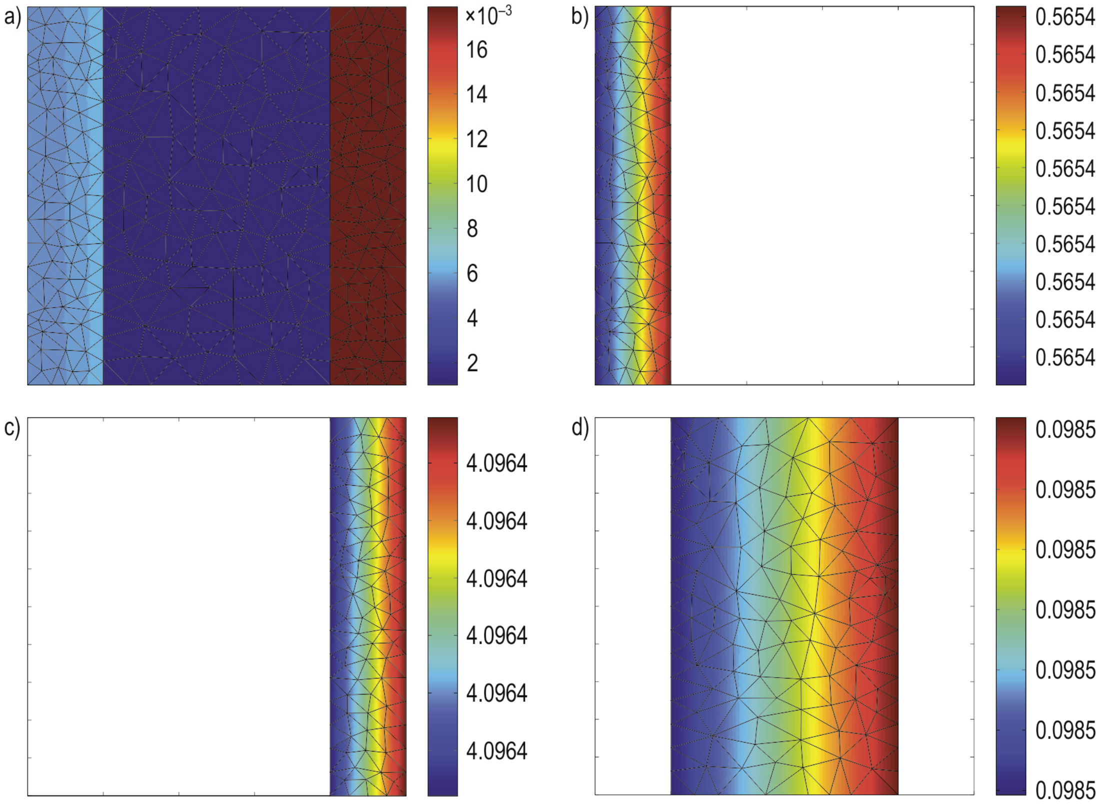

*Fig. 9. Contours of the lithium ions concentration (a) and potential in anode (b), cathode (c), electrolyte (d) at time 1000 s [9]*

Contours shown in Fig. 9b-d have similar values within each considered component of the battery. It means that there are no significant changes of potential inside the anode, cathode and electrolyte. The results make sense when the obtained values become referenced to the initial conditions i.e. initial potential for the electrolyte was zero [9], whereas the contour depicts a constant value of 0.0985 V. It means that the potential in the electrolyte increases as an effect of electrochemical processes in battery.

## Summary

On the basis of the literature review focused on the experimental tests on batteries it can be concluded that at the present moment there is no clearly defined standard of the battery testing especially those designed to be applied in non-typical kind of hybrid vehicles i.e. hybrid shunting locomotives. There are some standards relating to the battery application in consumer electronics and hybrid cars. However, there are no such standards for railway vehicles generally. In case of numerical analyses, the range of available studies is much wider and includes structural, thermal, electro-thermal or chemical analysis. However, both experimental studies and numerical analyses require a cooperation of experts from various fields such as mechanics, electronics and chemistry.

Above-mentioned inconveniences have forced the authors of this study to develop their own test procedures for the batteries proposed to be applied in the hybrid locomotive. The results of complex experimental tests carried out on the real diesel-electric locomotives were the starting point in developing the battery testing procedures. Tests carried out on sidings provided information on, inter alia, the temporary power demand. It allows the authors to determine value of the battery load current. The results of siding and battery tests will be presented in further work.

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