LITHIUM-ION BATTERY BEHAVIOUR CONSIDERING DIFFERENT OPERATING PARAMETERS

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Li-ion batteries are essential electrical systems equipments, occupying an important position in the automotive industry as well. They serve as a source of energy and as energy storage devices and for this reason their behaviour in relation to temperature represents a particularly important aspect. The current work proposed the numerical analysis of a battery made of 18650 Li-Ion cells, considering a series of parameters. Using 3D models made in COMSOL Multiphysics, the temperature variation in such a battery was followed, varying the number of cells, their positioning inside the battery, as well as the distance between the cells. Air cooling was considered, and the simulations led to a solution with 8 cells, positioned at 27 mm between them and positioned in a standard honeycomb shape.

Keywords: Li-Ion battery, thermal modelling, electromagnetic model, COMSOL simulation

1. Introduction

Lithium-Ion (Li-Ion) type batteries are used in almost any electrical power system (EPS) as the main storage device systems (SDS) starting from household applications to orbital satellites [1, 2]. These kinds of batteries are the most common in the automotive industry [3, 4]. Their versatility, good thermal stability and relatively low price have imposed them on the market in the last decades. Lithium-ion batteries have the advantages of high energy density, low self-discharge rate, long cycle life, and are also friendly to the environment [5, 6].

During an operation cycle, the battery experience charging and discharging rates which determinate increasing of their surface temperature [7, 8]. Two aspects define the optimal performance of the Li-Ion battery: (1) the optimal operating temperature range, which determines the temperature range in which a battery cell

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maintains its longest life cycle through an optimal charge-discharge cycle; (2) the maximum difference between the temperatures of the two battery cells for relatively uniform charge-discharge rates [9-11].

The Li-Ion battery optimally operates in a range of 15 – 40 ºC (288 – 313 Kelvin) and has a maximum temperature difference between battery cells of 5 ºC. The essential role of maintaining an optimal temperature of the batteries is fulfilled by the battery thermal management system (BTMS) [7, 12]. Li-Ion batteries come in various shapes and dimensions, but the most used are the prismatic batteries and cylindrical batteries [13]. Prismatic batteries can match energy from 20 up to 100 cylindrical batteries due to their bigger dimensions. Although cylindrical batteries store less energy, they deliver a more powerful performance, because they have more connections per ampere hour (Ah) [14].

Although they do not have the best energy/volume ratio, cylindrical batteries are still used in the automotive industry. The most used models are the Tesla 4680 [15] and the standard 18650 Li-Ion Cell [16]. The proposed paper presents a study of an electric battery with forced cooling using air. A series of parameters were varied, such as the number of cells in the battery, their position, as well as the distances between the cells, monitoring their thermal efficiency.

2. Materials and models

The chemical reactions that take place inside a Li-ion battery are presented in the specialty literature [17]. Each cell is designed to keep the cathode and anode separate to prevent a reaction. When the circuit is closed, electrons are attracted to the cathode (e.g. $LiCoO_2$ in lithium-ion batteries) traveling away from the electron rich anode (e.g. lithium-graphite) through the wire in the circuit to the cathode electrode.

Through a 0 to +1 oxidation state lithium is oxidized from Li to Li+ in the lithium-graphite during discharge, through the following reaction [17]:

$$C_6Li \rightarrow 6C(\text{graphite}) + Li^+ + e^- \tag{1}$$

The lithium ions then migrate to the cathode through the electrolyte, where they are incorporated into lithium cobalt oxide (which is reduced from a +4-oxidation state to a +3-oxidation state) by the following reaction [17]:

$$CoO_2\ (s) + Li^+ + e^- \rightarrow LiCoO_2\ (s) \tag{2}$$

The total chemical reaction can be summarized as follows (left to right = discharging, right to left = charging) [17]:

$$C_6Li + CoO_2 \rightleftarrows C_6 + LiCoO_2 \tag{3}$$

From the point of view of the equivalent circuit of a battery cell, the specialized literature proposes a series of equivalent circuit schematic schemes [18].

The simplest variant is a Thévenin equivalent circuit model (Fig. 1). This one composes an internal resistance (R_{int}) in series with a DC voltage source (v_{OCV}), which represents the open circuit voltage (OCV), considering Depth-of-Discharge (DoD) mathematical model. For the self-discharge effect, a resistance R_{sd} could be connected to the battery terminal during rest periods.

The second approach is an external C-rate model [18, 19] considering two different internal resistance (R_{int_cha} for the charging state and R_{int_dis} for the discharging state). Also, the second DC voltage source $\Delta V_{OCV}(T)$ is connected in series – this OCV correction term considers for the variation in OCV induced by temperature changes.

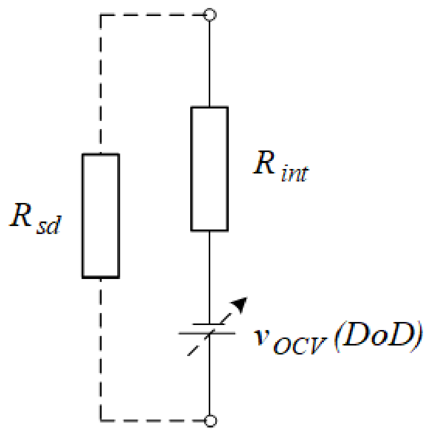

Fig. 1. Thevenin battery model [18].

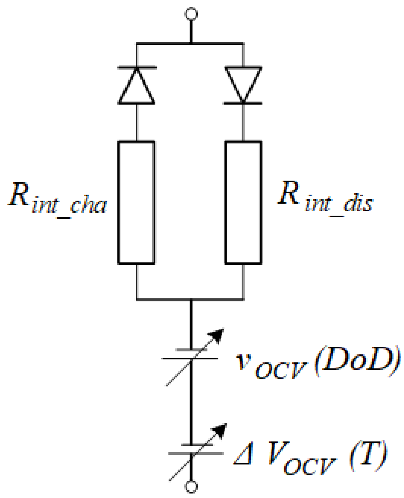

Fig. 2. Extended Thevenin battery model [18, 19].

In this paper, a computational simulation of a lithium-ion battery being cooled by the laminar flow of air around is illustrated. The simulation attempts to study the temperature increase of cells during charging and discharging Consequently, the effectiveness of cooling these cells using an active agent is examined. In our further computation, air is used for cooling. Each cell consists of the negative electrode, the positive electrode, and a separator. The negative electrode is built of Li_xC_6. The positive electrode is made of $LiMn_2O_4$, and the electrolyte is composed of $LiPF_6$.

The COMSOL model [20] presented herein is modeled after a cylindrical lithium-ion battery. The battery cells are encased within a cubic container and then cooled with air and a laminar model was imposed (volume flow was 0.8e-6 m3/s). There are several methods of cooling down a battery cell, and newer, more complicated implementations are being conceived. In this simulation, however, the cells are positioned in a case with an average distance of 0.027 m between them, air is let in though one inlet area and the air is exited though the opposite area. The model uses air to cool down the cells in the cubic container. The entry area and exit area are referred to as inlet boundary and outlet boundary respectfully. The model is built to have one inlet and one outlet of the same size. The introductory temperature of the air is maintained and measured against the air temperature at the exit. The dimensions of the battery cell modeled in this report are made to resemble 18650 cylindrical lithium-ion battery (Fig. 3). A capacity of 2500 mAh was considered, which is typical for this type of battery.

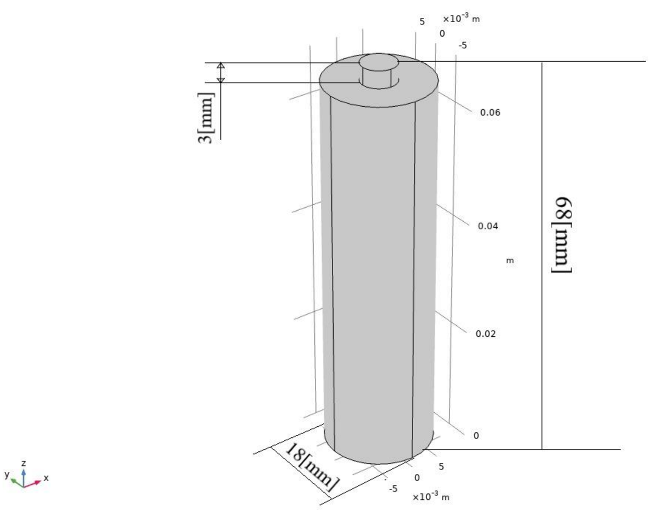

Fig. 3. One 18650 cell with dimensions used in COMSOL models.

3. Simulations varying different parameters

This part of the paper will analyse the temperature variation in different situations.

3.1. Different number of cells considered

First part of the study focuses on the air flow in the battery considering different number of cells. The analysis looks at three situations: 3-cells (Fig. 4), 5-cells (Fig. 5) and 8-cells (Fig. 6), respectively. It can be observed that for the same air flow speed, the second or the third row of the battery suffer a significant increase in temperature.

Our simulations were performed using a 2.5 GHz CPU with 16 GB RAM. In the model, flux boundary conditions were used for the inlet and outlet boundary. The total number of vertices in the mesh of the model was 15592 for the 3-cell model and 24978 for the larger 8 cell model. The number of tetrahedra to build the mesh was 24543 for the 3-cell model and went up to 49438 for the 8-cell model. The simulation time spanned between 20 minutes 17 seconds to 46 minutes 36 seconds.

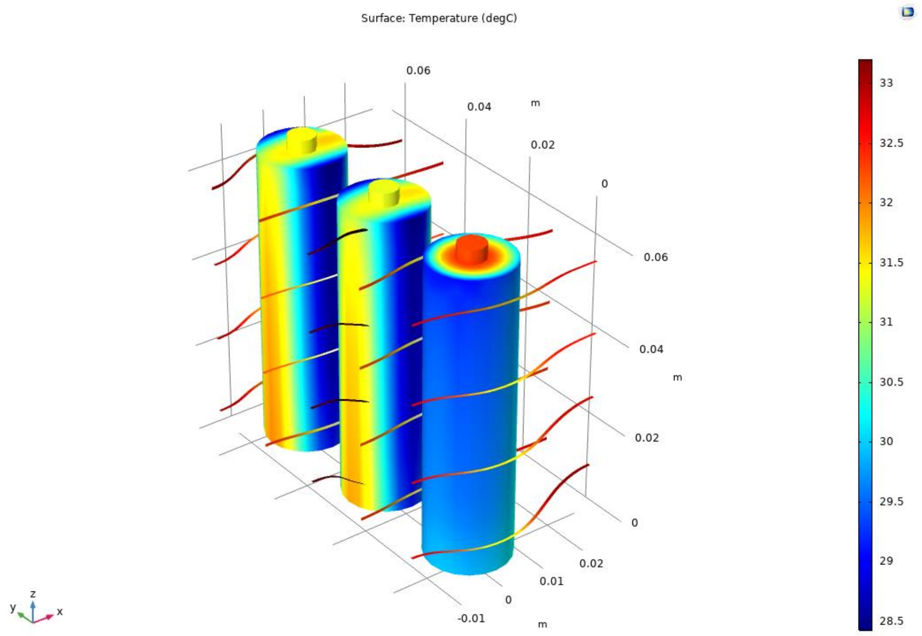

Fig. 4. The temperature spectrum for a 3-cell battery.

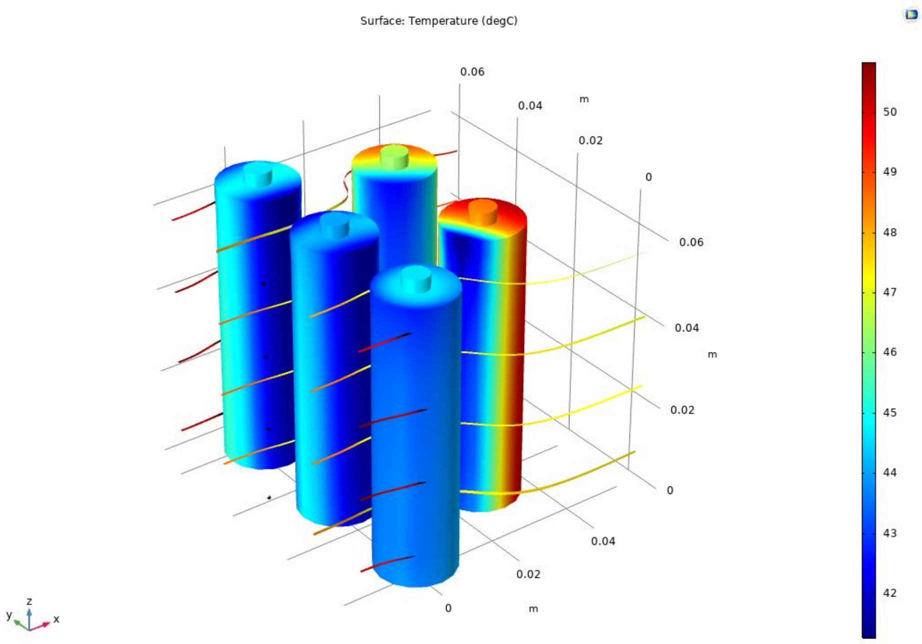

Fig. 5. The temperature spectrum for a 5-cell battery.

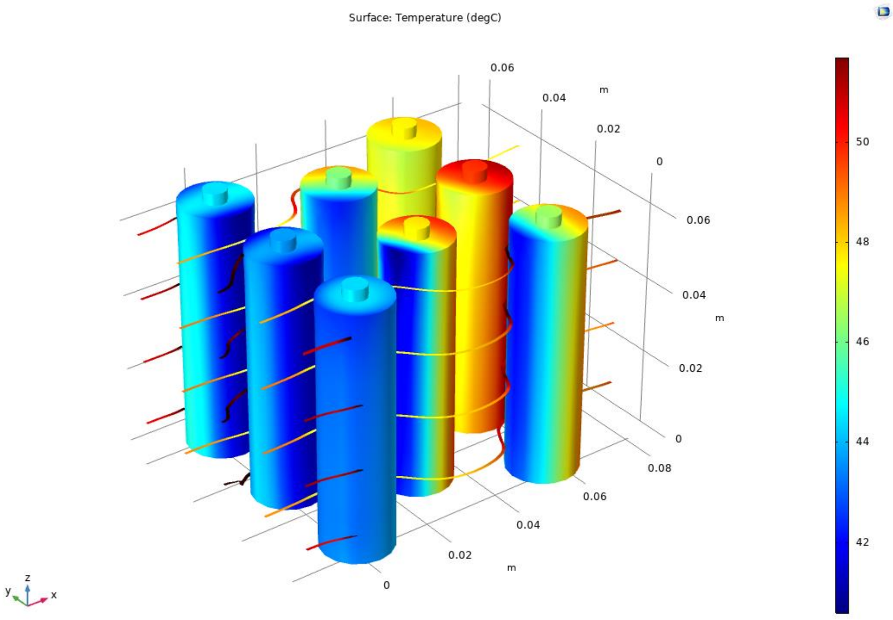

Fig. 6. The temperature spectrum for a 8-cell honeycomb battery.

To emphasize the differences, Fig. 7 depicts a comparison between the average temperature differences in the cells, considering reference temperature of 298.15 Kelvin (25^0 C), due to the charge-discharge cycle. It is obvious that increasing the number of rows in the battery will cause an increase of the temperature over 20^0C. However, the difference between the case with 5 cells (2 rows) and with 8 cells (3 rows) is not significant.

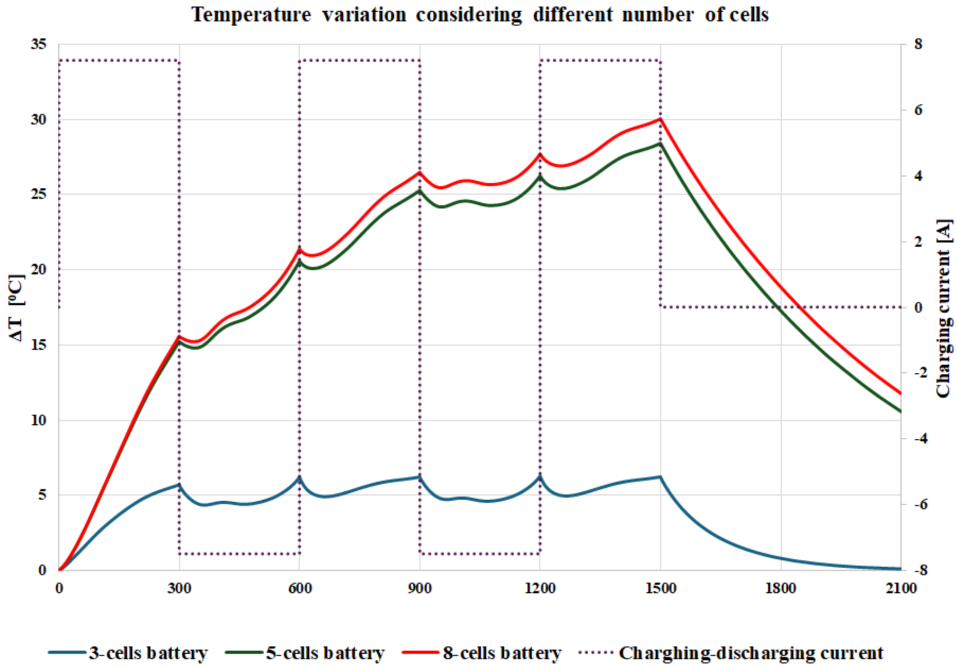

Fig. 7. Temperature difference for different number of cells in the battery.

3.2. Considering different cell positioning in the battery

The next aspect studied is the position occupied by the cell in the battery considering 8 cells. For this aspect, two situations were chosen: the above presented honeycomb (HC) and then new one in line (IL) (Fig. 8). It can be observed that the second row of the cells have a higher temperature. Also, in Fig.9 a comparison between these two cases is illustrated. For the IL situation the temperature is significantly higher.

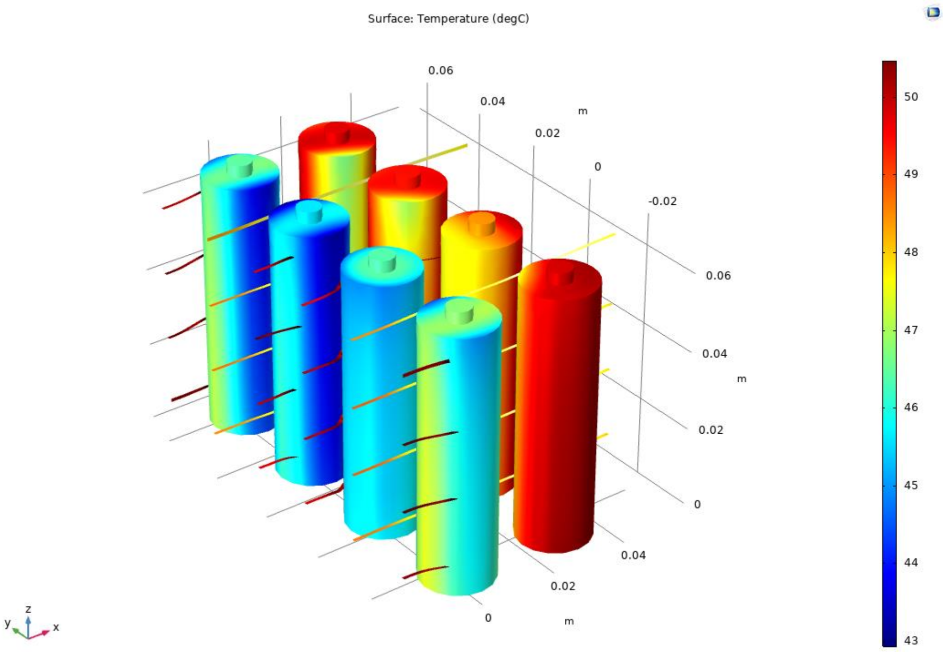

Fig. 8. The temperature spectrum for an 8-cell in line battery.

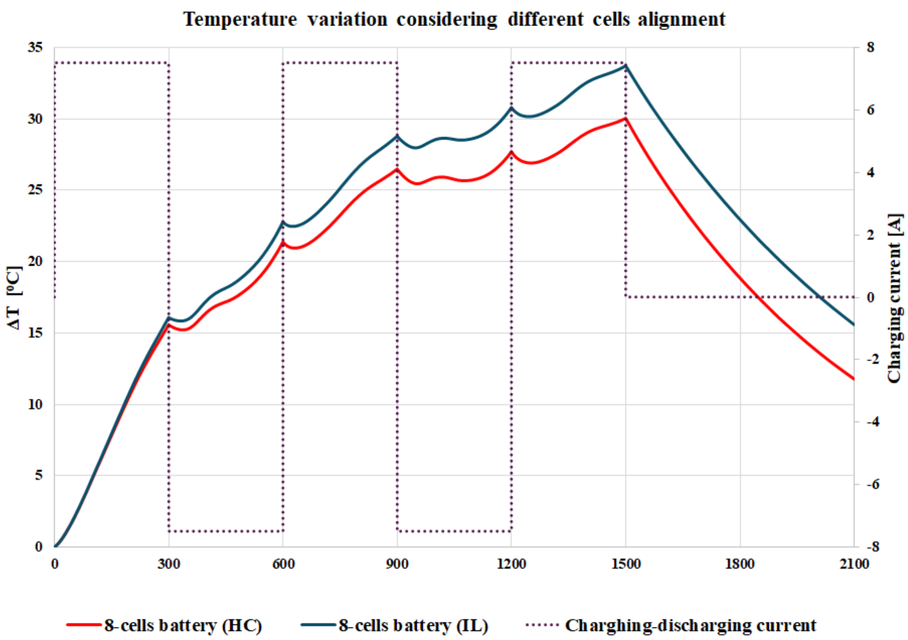

Fig. 9. Temperature difference for different alignment of cells in the battery.

3.3. Different distance between the cells in the battery.

The last part of the study focused on the influence of the distance between the cells in a battery. We have considered the 8-cells honeycomb case and varied the distance with ± 12 mm between the cells starting from the standard situation presented above (Fig. 6). In fig. 10 and 11 the numerical results generated by these two situations are depicted. Reducing the distance between the cells leads to a worse air flow and therefore to poorer cooling of the cells.

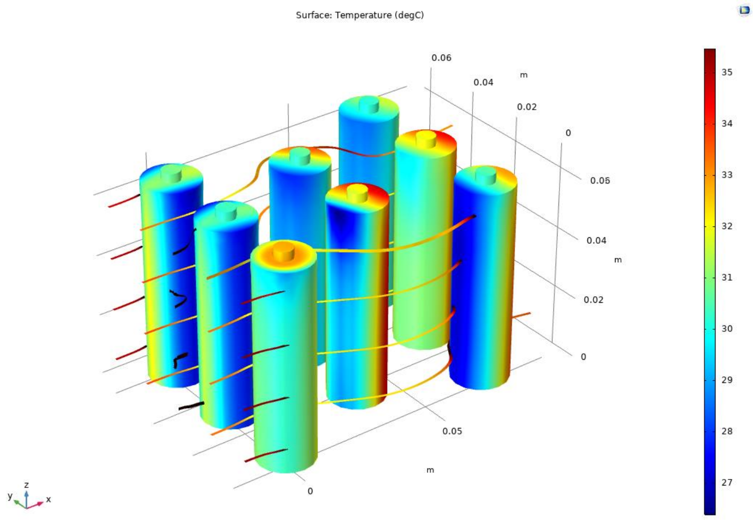

Fig. 10. The temperature spectrum for 8-cells honeycomb battery with the increase of the inter-cell distance with 12 mm.

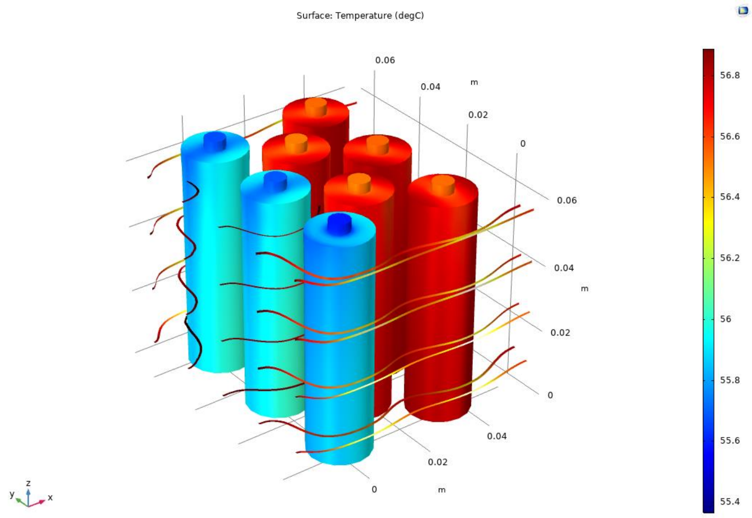

Fig. 11. The temperature spectrum for 8-cells battery in honeycomb arrangement with the decreasing of the inter-cell distance by 12 mm.

In Fig. 12 is presented a similar comparison between these three studied situations. It is obvious that a distance between the cells leads to a better flow of air between them (Fig. 12), but here, the most optimal solution should be chosen with respect to the resulting battery dimensions.

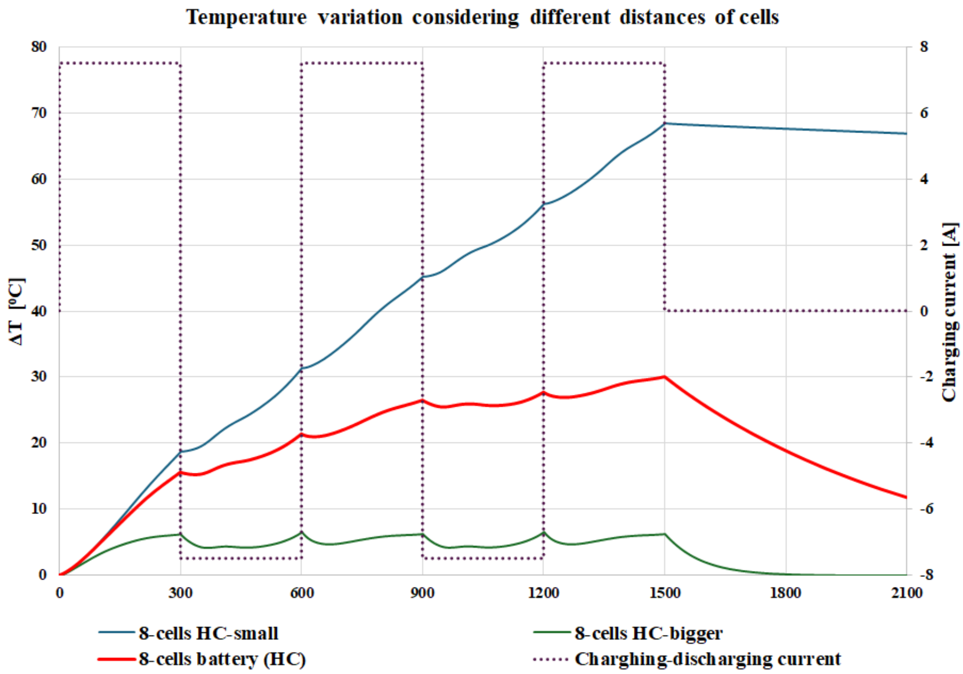

Fig. 12. Temperature difference for different distances between cells in the battery.

4. Conclusions

In this paper the influence of various parameters on the temperature variation in the case of a Li-ion battery was carried out. The analysis is a preliminary one to allow more complex studies to be carried out to optimize the operating of such a battery in the automotive field. Throughout the entire work, the cooling capacity of this air device was examined.

The first parameter studied is related to the influence of the number of cells in such a battery. Thus, it started with 3 (one row), then 5 (two rows) and finally 8 cells (three rows). Increasing the number of rows obviously leads to insufficient cooling. However, this aspect can lead to the choice of a more optimal cooling solutions (changing the environment, introducing more cooling outlets), solutions should be studied in the future.

Positioning a battery with 8 cells in a line or in a honeycomb structure, represents the second part of the study. The result here was as clear as possible in favour of the second solution, which must be adopted even if the number of cells in the battery is increased.

The last aspect of the study looked at the influence of the distance between the cells in a honeycomb battery. It turns out that a large distance between the cells is needed, leading to a significantly higher cooling. However, in this case, the technological limitations of the battery must also be considered.

The analysis may continue considering other aspects such as changing the cooling agent, multiplying the cooling outlets, e.a.

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