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Lithium-Ion Batteries with Forced Air Cooling: Simulation and Laboratory Tests

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***Abstract**: Sales and total population of electric vehicles are continuously increasing. Their production and maintenance should be supported by high amount of powerful and reliable battery cells. Various lithium-ion batteries comprise the major part of battery units for vehicles. This article is devoted to development of forced air cooling of battery module for hybrid tractor unit. Cooling of overall module has been significantly improved and temperature fields in all cells have been equalized by means of mathematical simulation. The model adequacy has been verified by laboratory tests of battery module of modified design. Temperature drop between single cells has been decreased more than by four times which reduces significantly probability of local overheating and thermal runaway. In the future the developed battery modules will be used in field tests of tractor unit with hybrid power unit.*

***Keywords**: hybrid electric vehicle, lithium-ion battery, cooling system, math modeling, finite element modeling.*

I. INTRODUCTION

Hybrid and electric vehicles become more and more popular every year reaching advanced levels. After scientific studies, electric-drive vehicles are in the mass markets which can improve environmental safety. Total fleet of electric-drive vehicles including electric cars and various hybrids, such as commercial vehicles and buses, reached 5.4 million in the third quarter of 2018. [1]. The growth dynamics of electric-drive vehicles is illustrated in Fig. 1. Statistical analysis of mid-sized and heavy commercial vehicles demonstrates that this fleet in 2018 reached 800 thousand.

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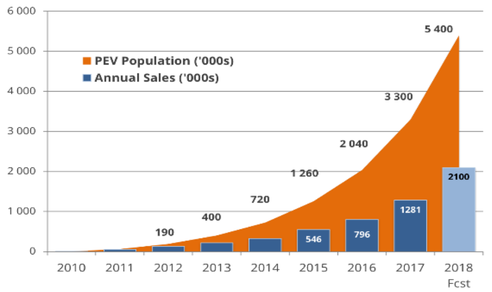

Fig. 1: Global plug-in vehicle population [1]

From 2011 to 2017 total capacity of produced batteries increased from 1 to 37 GW*h, which was the consequence of not only sharp increase in sales of electric vehicles but also of increase in capacity of batteries. Sector of lorries and buses contributed additional 26 GW*h in 2017. Additional market requiring for development of production of high capacity batteries can be presented by charging stations [2]. Electrochemical sources can provide rapid charging of electric-drive vehicles using existing networks. The major part of vehicle batteries is presented by lithium-ion cells, more than one half is comprised of Lithium Nickel Manganese Cobalt Oxide (NMC). Significant market segment is occupied by Lithium Ferro Phosphate (LFP) applied mainly by Chinese manufacturers, and Lithium Nickel Cobalt Aluminum Oxide (NCA) applied in Tesla cars. Other types of energy storage units lost their positions and are used quite rarely. Figure 2 illustrates the delivered battery capacity by cathode chemistry.

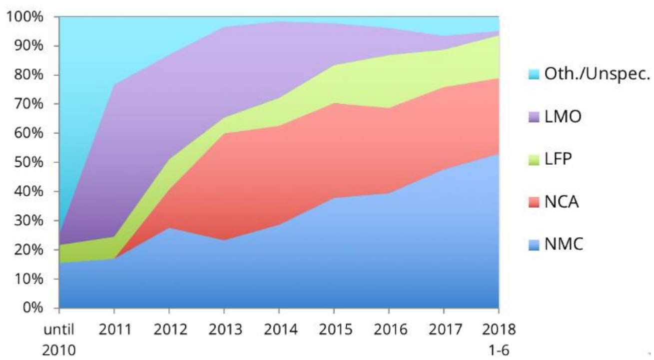

Fig. 2: Delivered battery capacity by cathode chemistry [1].

In high capacity batteries comprised of numerous lithium-ion cells, they are in apparently different temperature conditions. Without forced cooling, central cells are heated significantly higher than marginal ones [3], [4], which is related with mutual influence of neighboring elements.

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In the case of air or liquid forced cooling, additional influence is exerted by non-uniform distribution of heat transfer medium across single cells [5], [6].

This project was devoted to development of autonomous tractor unit with predictive control [7]. As evidenced by the overview [8], the predictive control is one of the most efficient control methods of power units, and numerous studies nowadays are devoted to hybrid vehicles since the problem of reasonable distribution of power streams is very important.

Simulation of the developed vehicle with sequential flowchart of hybrid power unit [9], [10] determined the required cumulative capacity of batteries to be about 20 kW*h. While developing high capacity lithium-ion batteries comprised of numerous cells, one of the most important issues is provision of uniformity and sufficiency of their cooling.

In the case of excessive heating of single cell, it can fail due to temperature overrun which is extremely dangerous for the battery. It is impossible to control the state of each cell or even its constituents in large battery, as in laboratory tests. Hence, theoretical study and simulation of cooling systems of lithium-ion batteries are important.

II. DESIGN OF BATTERY MODULE

The developed battery is intended for tractor unit with hybrid power unit. It is comprised of 42 lithium-ion cells (NMC), their specifications are summarized in Table 1. All cells are connected in series, the developed design of tractor unit includes three such battery modules.

Table 1: Cell specifications [11]

Items	Specifications	Items	Specifications
Nominal Capacity	40 [Ah]	Maximum Charge Voltage	4.2[V]
Nominal Voltage	3.7 [V]	Lower Voltage Limit for Discharge	2.7[V]
Cell Dimensions	Length: 220 [mm] Width: 215 [mm] Thickness: 9 [mm]	Recommended Charge Current	40[A]
Operation Temperature	Charge: 0 ~ 40 [°C] Discharge:-20~60 [°C]	Continuous Discharge Current	40[A]
Weight	0.935 [kg]	Maximum Discharge Current	200[A]

Electrical terminals of all cells are connected by means of one board made of insulating material and special clamps. The module body is comprised of metal frame and two plastic casings: external protecting one and internal one directing air flows. Air for cooling of cells is supplied by radial fan into the cavity formed by plastic shells and then into gaps between the shells. Air passes along the cells upwards and accumulates thermal energy generated during charging or discharging. Hot heat carrying agent is removed from the module into environment. Design of the developed battery module and flowchart of its cooling are illustrated in Fig. 3.

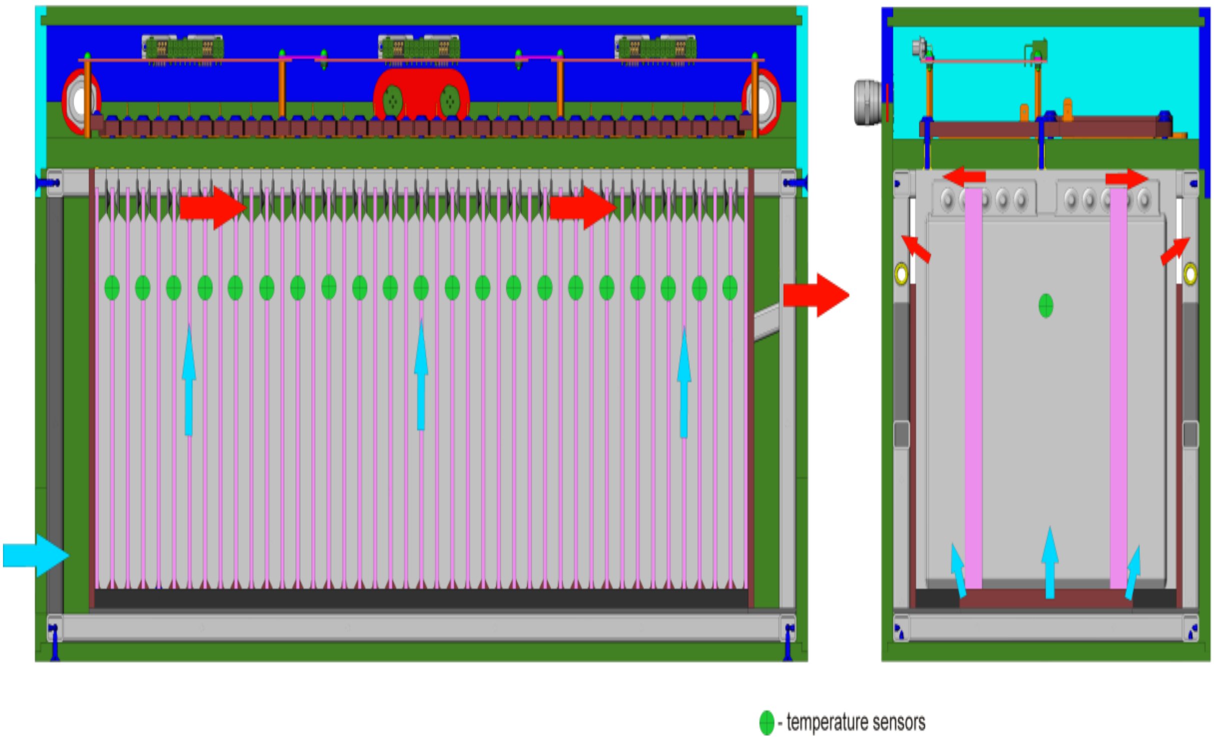

Fig. 3: Battery module design and cooling flowchart.

The boards of battery management system (BMS) are located in the upper part of battery module, they control voltages and temperatures of individual cells. The number of temperature sensors is two times lower than that of cells, however, their uniform distribution and position in the most heated area provide the most efficient temperature control. Figure 4 illustrates battery module without upper cover.

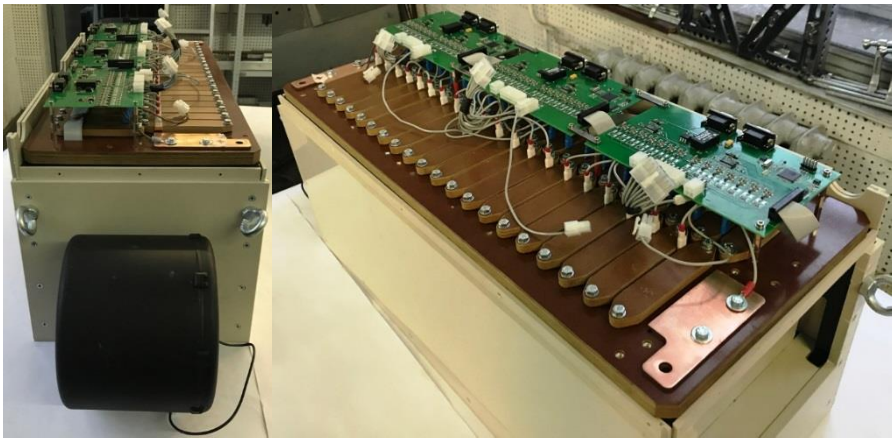

Fig. 4: Battery module without upper cover.

Operability of the developed battery module was verified by laboratory tests comprised of subsequent discharge by various currents, temperature sensor readings were monitored during these tests. Discharge currents were from 1C (40A) to 5C (200A) and the testing duration was from 1 h to 10 min. Maximum heating of battery was achieved at discharge current of 200A which is an extremely severe test, since such modes are unlikely upon operation in vehicles.

It was revealed that, despite that the average air temperature between the cells did not exceed 37°C, the maximum temperature for three sensors was 54°C. Therefore, several cells were heated by 17°C above average temperature. Hence, some cells operate at upper boundary of temperature range. The measured air flow rate was about 160 m^3/h during total loading cycle at ambient temperature of about 20°C. Figure 5 illustrates experimental results of battery module at medium and maximum temperatures achieved at various currents.

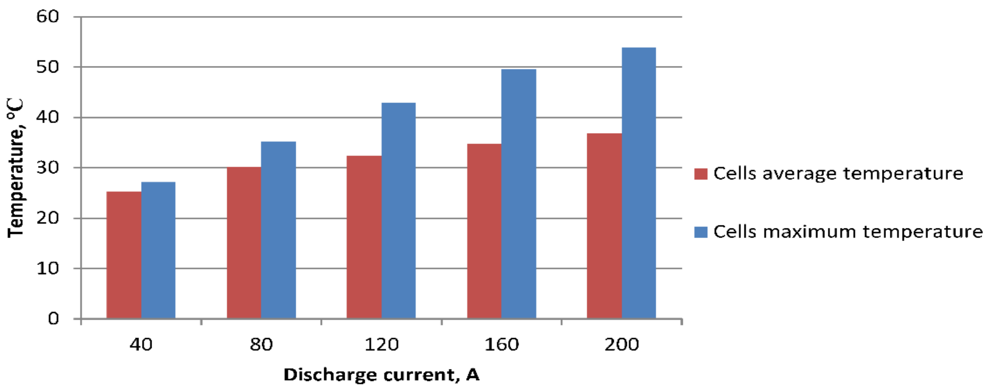

Fig. 5: Tests of battery module.

Overheating of even one cell in battery module can lead to undesired consequences. At minor overheating to 60-65°C, only cell lifetime is decreased significantly [12], thus, the overall battery capacity. Upon cell heating from 65°C to 80°C, in addition to decrease in lifetime, internal pressure increases which can lead to deformation of internal structures and internal short circuit [13]. In its turn, this would lead to inflammation of element and overall battery. This can occur when no protecting valve is provided in the batteries. Even without short circuit the element cannot be used any longer and, depending on type of mechanical damages, can destroy overall battery.

Therefore, the obtained experimental results of the developed battery module and danger of excessive overheating of constituent cells define the importance of theoretical study of temperature distribution across cells upon selected type of cooling and design. Such study could be simulated using external conditions and cell specifications determined during laboratory tests.

III. SIMULATION METHODS

The cooling system of battery module in this work was simulated by the finite element method as the most widely applied numerical method. Taking into account the dimensions of the developed battery module (675*288*343mm) and the required accuracy, total amount of finite elements was about 5.7 million.

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In order to obtain spatial discretization, rectangular grid was used and the Cartesian cells were applied near boundaries, i.e. near boundary cells were polyhedrons with arbitrary oriented plane faces. For more accurate predictions of air parameters in narrow gaps between the cells, smaller finite elements were used than in the model.

The main processes considered upon simulation of battery module cooling were heat conductance in solids, forced heat exchange between solids and air, as well as variations of thermodynamic air properties in various points of flow. Aiming at simplification of calculations, such non-essential phenomena as gravitation, casing heat loss to environment, radiative heat exchange and others were neglected. Heat transfer to air was determined by the energy conservation equation.

Each cell was heated non-uniformly, which corresponded to tests and simulation of similar objects [14], [15]. Herewith, cumulative heat energy released during cell operation was selected in this study so that the simulation results were as close as possible to the experimental measurements. This is required due to complicated dependence of cell operation efficiency on discharge current and temperature. During simulation of heat and mass transfer, the boundary conditions were air flow rate across the module (160 m^3/h) and output atmospheric pressure, initial air temperature (20°C) and properties of materials of casing and cells. All initial and boundary simulation conditions were fixed for overall study in order to provide comparison of various variants of battery module design in terms of homogeneity of temperature field of lithium-ion cells.

Further on, the battery module design will be modified based on simulation of heat transfer so that to provide uniform cell cooling. A new battery module will be tested under conditions as close as possible to initial conditions in order to verify significance of modifications.

IV. SIMULATION RESULTS

It was determined during simulation of heat exchange in battery module that under similar experimental conditions, the maximum temperature of the cells reached 58°C, which was close to maximum allowable conditions. In addition, the obtained distributions in various sections demonstrated that the cells #5-14 were the most thermally loaded, the count was carried out from cooling air supply. Figure 6 exemplifies the obtained predicted temperatures in longitudinal cross section of the battery module.

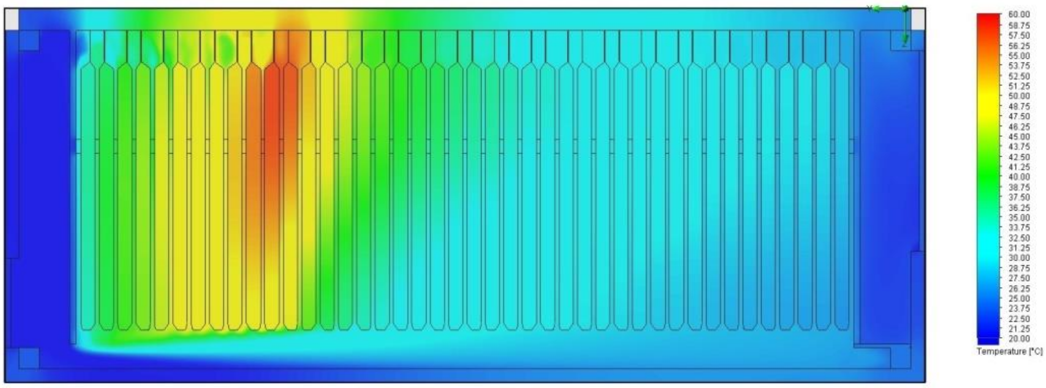

Fig. 6: Predicted temperatures in longitudinal cross section of battery module.

Not only the temperatures of lithium-ion cells were predicted but also air temperatures in the sensor locations. This allowed direct comparison of simulations and tests. Aiming at comparison of simulations and laboratory tests, Fig. 7 also illustrates air flow rates across channels between the cells. Distribution of air flow rates across individual channels will allow to determine the reason of cell overheating and to perform appropriate modifications in the module design. Actual and predicted temperatures coincide with high accuracy and the highest differences do not exceed 3°C. The difference between the maximum and the minimum air temperatures of the battery cells was higher than 33°C.

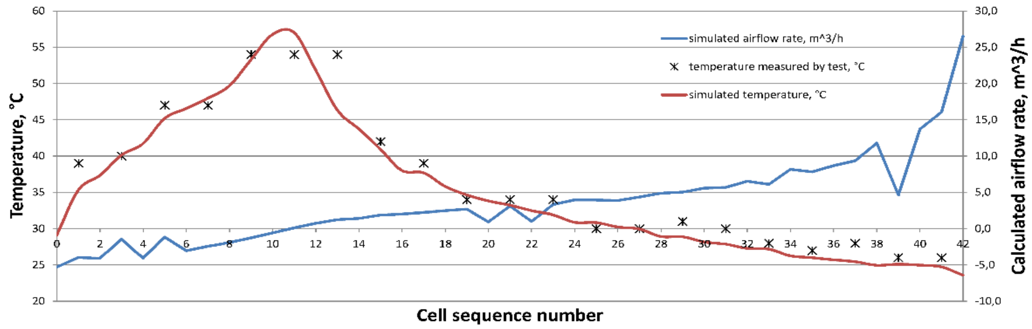

Fig. 7: Comparison of simulations and laboratory tests.

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As follows from the data in Fig. 7, the first five cells of the module are located in the region of reverse flow, that is, the negative air flow rates mean that air moves downwards and is then mixed with supplied cold air, thus impairing the module cooling. This can be attributed to generation of area of lower pressure behind the front panel of internal casing.

It should be mentioned that the air flow rate in the gaps between the cells from #8 to #15 is lower than 3 m^3/h, which is the main reason of overheating. Generally, air is distributed across overall module highly heterogeneously, thus resulting in heterogeneous cooling. Steady vortices occurring in air inlet and outlet should be mentioned separately, which can have significant effect on its aerodynamic resistance which equals to 575 Pa. Decrease in pressure drop will correspond to increase in cumulative air flow rate and more intensive cooling.

After analysis of simulation results, the battery module design was modified with the aim of optimization of forced air cooling illustrated in Fig. 8:

1) additional plates at air inlet and outlet aiming at elimination of vortices;

2) cutoff at the front panel of internal casing in order to eliminate reverse air flow in initial cells;

3) additional parts and tapering of side wall panels of internal casing in order to provide variable channel cross sections.

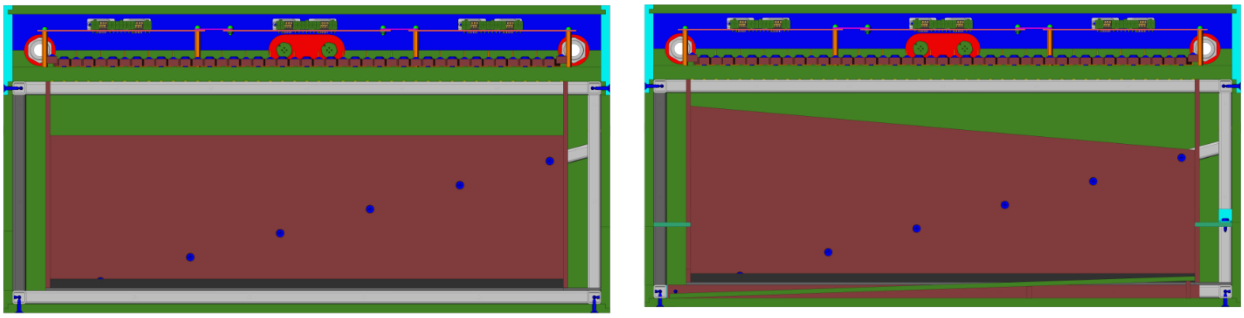

Fig. 8: Initial (at the left) and modified (at the right) design of battery module.

During simulations based on modified geometry of battery module design, it was detected that the air flow rate and temperature became more uniformly distributed. The difference between the maximum and minimum air temperatures of battery cells was lower than 18°C and aerodynamic resistance decreased by 10% equaling to 522 Pa. Simulation results and temperature distribution in longitudinal cross section of the module are illustrated in Figs. 9 and 10. It can be seen that the maximum temperature of cells was slightly higher than 40°C.

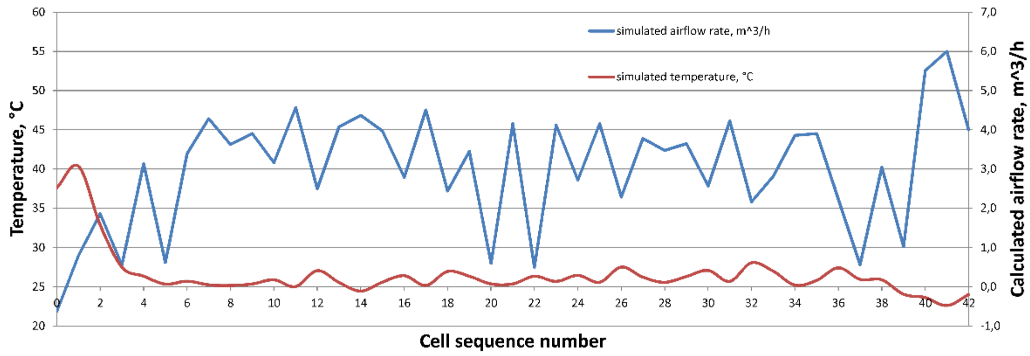

Fig. 9: Simulation results of adjusted battery module

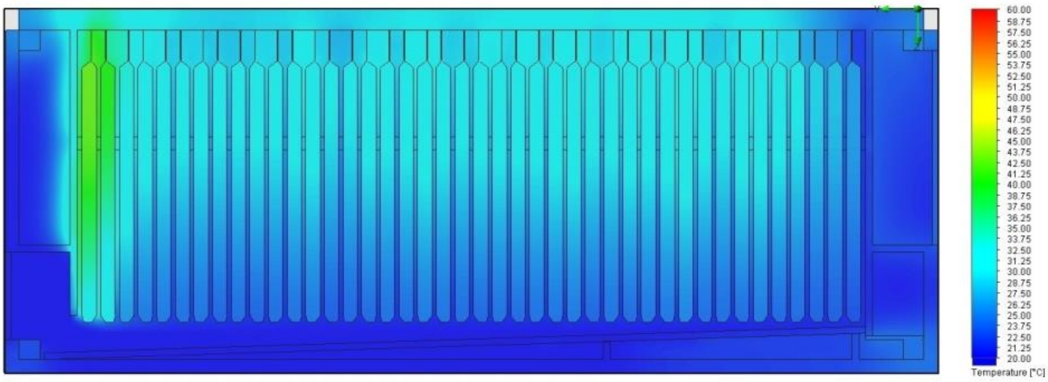

Fig. 10: Predicted temperatures in longitudinal cross section of modified battery module

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V. RESULT AND DISCUSSION

Simulations of thermal process with subsequent tests are widely used for verification or adjustment of the obtained results [16], [17] being powerful tool for rapid and high quality designing of various devices including vehicles.

The developed 3D models were used for manufacturing of new and modified parts and one battery module was assembled for laboratory tests. The main modifications were related to internal casing of the module since it plays decisive role for redistribution of heat carrier. The initial and new designs of internal casing are compared in Fig. 11.

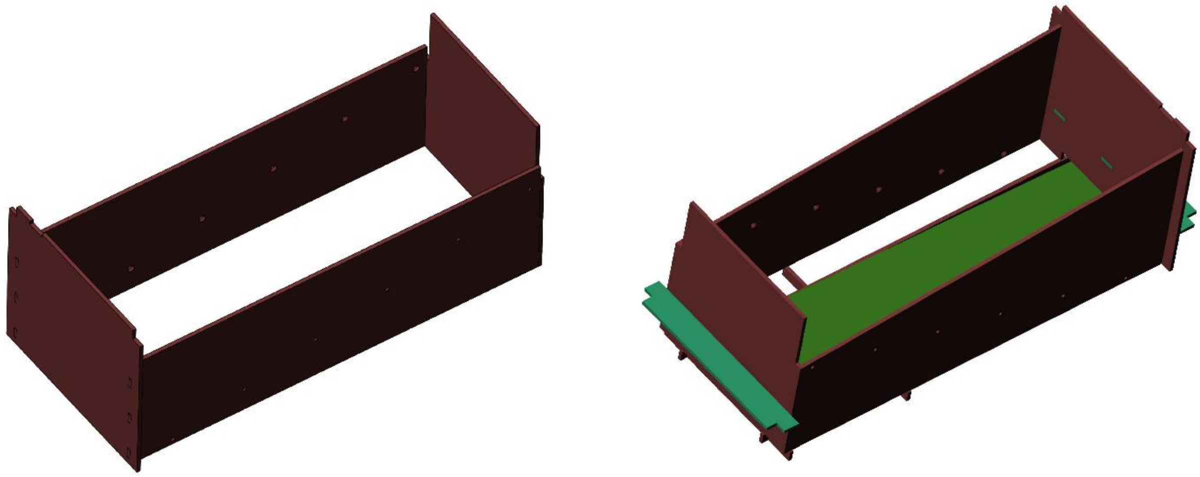

Fig. 11: Comparison of initial and new designs of internal casing.

During experiments, the discharge current and ambient temperature are the same as in initial tests. Due to decreased resistance of the module, the air flow rate increased slightly amounting to 163-164 m^3/h. Average temperature according to 21 sensors was 26.2°C, which was significantly lower than previous test results. It can be seen in Fig. 12, where temperature distributions across the cells of modified battery module are compared for simulations and experiments, that for all sensors except for the first one, the differences are less than 2°C. Significant divergence of simulations and experiments for the first sensor requires for additional explanation.

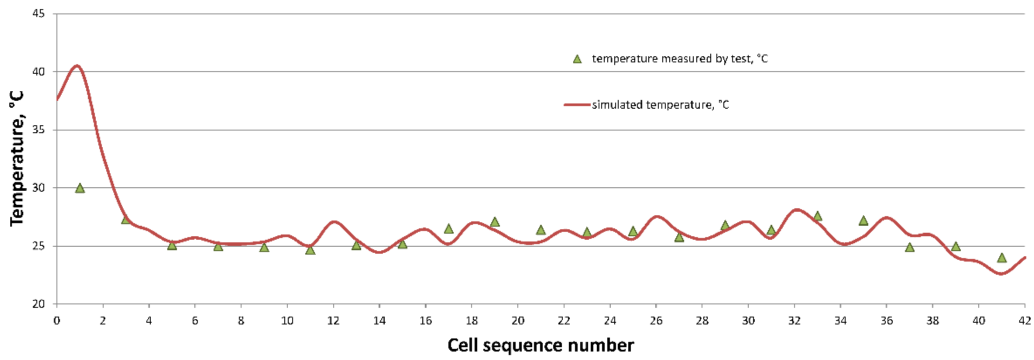

Fig. 12: Comparison of temperatures distribution across the cells of battery module based on simulation and experiments.

Taking into account good convergence of simulation and experiment, prediction errors can be neglected. Verification of temperature sensor did not reveal meaningful deviations of its accuracy and sensitivity, which automatically eliminates error of laboratory measurements. This divergence between model and experiment could be reasonably attributed to unsuspected deviations of module casing parts and, which was more important, of battery cell geometry. The cells used in this work have flexible shell made of polymers. During assembling of cells in the module, some of their constituents can be deformed and effect on distribution of air flows. Additional influence can be exerted by unaccounted heat transfer via contact plates between adjacent cells. Despite minor deviations from the model, modification of battery module design made it possible to decrease maximum and medium temperature of cells at high discharge currents. This provides protection against overheating and temperature overrun during operation.

VI. CONCLUSION

Electric vehicles become more and more popular. High capacity battery modules required for energy storage from external or internal charging devices are comprised of numerous battery cells. Upon mutual operation of numerous electrochemical cells, it is important not only to release excessive thermal energy but also to provide uniform cooling.

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Non-uniform cooling can impair operational properties or lead to overall failure of battery module.

Extreme cooling non-uniformity was detected for the developed module. At maximum allowed charge currents and high ambient temperature, single cells could be damaged. In order to reveal the reasons of overheating, air cooling system was simulated, the design was modified, and the modified module design was tested in laboratory.

The implemented modifications made it possible to decrease both medium and maximum cell temperature, which improved cooling and reduced probability of module failure. In the future the developed battery modules will be used in field tests of tractor unit with hybrid power unit.

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