SIMULATED THERMAL RESPONSE OF A BATTERY PACK USED BY ELECTRIC TWO-WHEELERS

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This article presents a theoretical investigation into the thermal behavior of a pack of 18650 lithium-ion commercial batteries used for the propulsion of two-wheeled electric vehicles. In the first part, we highlight the theoretical aspects that describe the energy balance of a cylindrical lithium-ion battery based on the law of conservation of energy. The research aims to emphasize the effect of temperature on the technical performance of batteries. Next, using the COMSOL Multiphysics 6.2 software package, "Heat transfer in Solids and Fluids", the thermal behavior was modeled for a single cylindrical battery cell, type 18650 lithium-ion, 3.7V, 2200mAh, respectively a battery pack with the same type of cells, 18650 lithium-ion. The battery pack was made in the structure of 3 cells in series and 7 cells in parallel - 3S7P. The distribution of the temperature generated inside the battery cell, respectively in the structure of the 3S7P battery pack, was taken into account, at a charge/discharge rate considered extreme of 5.5C. In order to ensure a quality mesh in the process of simulating the geometry of the 3S7P battery pack, a mesh convergence study was also considered through progressively finer runs until the temperature of the battery pack did not change significantly with the subsequent refinement of the mesh. Simulations of thermal behavior were conducted while accounting for thermal conductivity, density, heat capacity, and heat source in the batteries. The battery pack was thermally loaded to measure temperatures inside the protective case, starting from an initial ambient temperature. The results obtained demonstrate several characteristics that can enhance the technical performance of battery packs used in electric two-wheeled vehicles.

Key words*: simulation; cylindrical lithium-ion batteries; thermal stress; energy transfer*

1. Introduction

Climate change, the depletion of fossil fuel reserves, but also the increase in pollution are a vital problem at a global level [1]. The European Union's policies on greenhouse gas emissions aim for climate neutrality by 2050, and their reduction should reach at least 55% by 2030 compared to 1990 levels [2]. Achieving climate change mitigation goals would require changes in societal behaviors, but also in technologies that would phase out the use of polluting energy resources. In this regard, finding new sources of green energy, but especially technologies for storing this energy, is a global concern both

among researchers and manufacturers of equipment and technical devices specific to the automotive industry. In this direction, numerous energy storage technologies (mechanical, electrochemical, thermal or chemical) [3] are known, with different energy capacities and charge/discharge times [3, 4], but also with a certain impact on the environment [5-8], thus resulting in several types of storage devices: flywheels, compressed air, hydro-pumping, batteries (lead-acid, lithium-ion), flow battery, double-layer capacitor, superconducting magnets, hydrogen and molten salts [9], [3].

Among the energy storage technologies that are gaining popularity, have relatively low costs, high autonomy, and also technological advances in implementation, the most promising seem to be electrochemical storage technologies. In this category of technologies, we find batteries with lead acid, nickel, sodium-sulfur, lithium batteries, and flow batteries [10]. Energy stored in batteries finds its availability in commercial, residential, agricultural, and industrial spaces. According to the report [11], batteries will be key to achieving the energy targets agreed by nearly 200 countries at the COP28 climate change conference in Dubai (the 28th United Nations Climate Change Conference), in particular tripling renewable energy capacity by 2030, doubling the pace of energy efficiency improvement and transitioning away from fossil fuels [12]. Due to the potential of energy storage systems, researchers' efforts are focused on identifying typologies, technical characteristics, limitations, comparisons, evaluations, challenges, but also applications aimed at using the best energy storage technologies [3].

One sector that seems to be using the potential of electric batteries is electric vehicles. As a solution to dependence on fossil fuels, the concept of "sustainable transport" is identified [13]. This can be achieved, as the use of electric vehicles in the transport sector would significantly reduce greenhouse gas emissions, contribute to an improvement in air quality [14], but would also eliminate some of the noise pollution produced by vehicles with internal combustion engines [15-17], in a word, they would be environmentally friendly. Moreover, compared to the fossil fuel-based propulsion energy source, in the case of electric vehicles (light, medium or heavy), electric batteries can be recycled, leading to an alleviation of environmental concerns [6].

If we consider the use of batteries for electric vehicles, then different requirements are imposed, which are given by the specific energy, power density, rated voltage, self-discharge speed, charging time, life cycle, operational safety, working temperature, cost price, etc. With a higher energy density (620 $kWhm^{-3}$), lithium-ion batteries are by far the high-capacity technologies for an improved implementation of energy storage in the built environment, even if the price is high [3]. However, batteries still present a number of obstacles to their introduction on the widest possible scale. These can be identified in the underdeveloped technology of electric batteries [17], the limited autonomy, the charging time, but also the expensive initial costs [20]. Extensive research is being conducted to tackle the challenges facing battery technology head-on. This research is driving the development of advanced technologies such as fast charging, optimization strategies [8], [21] intelligent charging systems [22, 23], and significant improvements in energy efficiency. Additionally, it addresses the practical limitations of wireless charging, modern algorithms for battery condition assessment, safety measures for high-energy batteries, and their environmental impact [7, 8]. Moreover, we have made substantial progress in voltage balancing of battery cells within battery management systems, employing various methods to ensure effective balancing during both the charging and proper discharge processes of battery packs [24, 25]. These efforts aim to improve the usability, reliability and general acceptance of different types of electric vehicles [26].

In this study, aspects regarding the thermal behavior of the commercial lithium-ion cylindrical battery type 18650, are treated [38]. The battery pack subjected to simulation contains 21 cylindrical cells, 18650, in 3S7P connection. The electrical connections between the cells of the battery pack were made with connectors made of zinc metal sheet, with a thickness of 0.5 mm. The length of the electrical connector for both series and parallel connections is 123 mm. The width of the series connector is 8 mm, and that of the parallel connector is 27 mm. The parallel connector element has 6 square cutouts with sides of 11 mm along its length. Also, the battery pack is inserted into a rectangular protective housing made of thermoplastic polymer (Acrylonitrile Butadiene Styrene).

In the first part, an analysis of the role, importance, and specific problems of batteries used in the automotive is presented, with a presentation of an analytical model on heat transfer for cylindrical lithium-ion batteries. The thermal response of the battery pack is presented, emphasizing the action of temperature on their performance. In the final part, a thermal modeling and simulation of the cylindrical lithium-ion battery using the COMSOL Multiphysics software package is presented, aiming at the results obtained to be interpreted in order to identify some points of optimization from a technical point of view of the battery packs used in the propulsion of 2-wheeled electric vehicles.

2. Analytical model for heat transfer

The thermal behavior of batteries is generally governed by three fundamental equations: the heat generation equation, the energy equilibrium equation, and the boundary condition equation [18, 19]. Based on these equations, there are a multitude of models that have proposed to study the thermal battery cells characteristics [19]. The concentrated capacitance model was taken into account in the analytical solution method for heat transfer in the battery cell [27]. The equation describing the energy balance of a cylindrical cell for a lithium-ion battery can be developed considering the law of conservation of energy. Under these conditions, the relationship of energy balance can be written as eq.(1), [27-29]:

$$\rho C_p \frac{dT}{dt} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_r r \frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k_a \frac{\partial T}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + \dot{Q} \quad (1)$$

In eq. (1) it is observed that the term on the left side represents the energy stored in the cell, while the term on the right side shows the three-dimensional conduction of heat, the expression of the rate of volumetric heat generation. Taking into account the constructive structure of a cylindrical cell in a lithium-ion battery, each cell of a battery module can be considered as a homogeneous body with effective thermophysical properties [27], [30]. In view of these considerations, the actual value of the density and thermal capacity of a single cell can be written as eq. (2), [27]:

$$\rho C_p = \frac{\sum_i \rho_i C_{p,i} V_i}{\sum_i V_i} \quad (2)$$

As the active material of the lithium-ion battery consists of one or more battery cells whose layers are spirally wound in a cylinder, the thermal conductivities are hypothesized to be thermally anisotropic, exhibiting a higher thermal conductivity along the battery sheets, in the direction of the length of the

cylinder, compared to the normal direction of the sheets, i.e. the radial one [31]. Under these conditions, the thermal conductivity in the radial direction is of the form of the eq. (3), [27], [30-32]:

$$k_r = \frac{\sum_i L_i}{\sum_i \frac{L_i}{k_{T,i}}} \tag{3}$$

and the thermal conductivity in the direction of the length of the cylinder is given by the relationship:

$$k_a = \frac{\sum_i L_i k_{T,i}}{\sum_i L_i} \tag{4}$$

Similarly, the density and specific heat capacity of the active material can be determined according to the eqs. (5) and (6), [32]:

$$\rho = \frac{\sum_i L_i \rho_i}{\sum_i L_i} \tag{5}$$

$$C_p = \frac{\sum_i L_i C_{p,i}}{\sum_i L_i} \tag{6}$$

Thermal modeling of concentrated capacitance is an approach to transient conduction that assumes that the temperature of a solid is spatially uniform and is only a function of time *t*. This implies that there are negligible temperature gradients in a solid and that the thermal conductivity *k* is infinite. In reality, this aspect is completely different, in the sense that it can only be approximated if the thermal resistance to conduction inside the solid is significantly lower than the thermal resistance to convection between the solid and the environment [19], [27]:

$$\frac{L_c}{k} \ll \frac{1}{h} \tag{7}$$

In the given case, the characteristic length *h* is the ratio of the volume to the surface area of the solid. In addition, eq. (7) formulates the dimensionless number Biot as in [18, 19], [27]:

$$Bi = \frac{hL_c}{k} \ll 1 \tag{8}$$

The ratio of heat transfer resistance within and to the surface of the battery cell is represented as *Bi* number, and it must be significantly less than 1 to be applied in a concentrated capacitance model. This is because when it is less than 0.1, the transient heat pattern error is less than 5%. When taking into account the parametric values of the current scenario, the number is also less than 0.1 [27]. If the *Bi* number is higher than 1, it means that there would be temperature gradients inside the body [18]. Under

these conditions, there is the alternative of applying the concentrated capacity model for the heat transfer of the lithium-ion battery cell by simplifying the equation of the global energy balance, as in eq. (9):

$$\rho C_p \frac{dT}{dt} = hA(T - T_{amb}) + \dot{Q} \tag{9}$$

The thermal balance for the recovery of the energy stored in battery packs used in the propulsion of 2-wheeled electric vehicles is a key to verifying their technical performance. From this mathematical analysis it is possible to identify the direction of optimization of the use of electricity stored in batteries.

In eq. (9), $\dot{Q}$ signifies the battery volumetric heat production rate [W]. There are several heat sources in a battery, mainly irreversible and reversible processes, that occur during its charging/discharging process. Irreversible heat is primarily due to ohmic resistance from the flow of electrons and ions and polarization resistance from activation and concentration changes, while reversible heat comes from electrochemical reactions and entropy changes at the cathode and electrode of the battery.

The total heat produced by the battery can be written as [29], [39]:

$$Q = Q_{irr} + Q_{rev} = I(V - U_{ouc}) + IT\frac{\partial U_{ouc}}{\partial T} \tag{10}$$

where Q is the heat of reaction, Q_{rev} is the reversible heat and Q_{irr} is the irreversible heat, I is the discharge current, V is the battery potential, T is the battery temperature, U_{ouc} is the open circuit potential, and $\frac{\partial U_{ouc}}{\partial T}$ is the entropic heat coefficient.

3. Modelling and thermal simulation of cylindrical Li-ion battery pack

The causes that determine the heating of electric batteries in the charging or discharging process are given by changes in enthalpy, resistive heating inside the cell, respectively electrochemical polarization. The change in enthalpy combined with the electrochemical reactions that occur inside the battery is the main cause of the increase in battery temperature [27], [29]. Following the analysis of the thermal balance equation, ohmic heat is identified as representing the energy loss caused by transport resistance in solid and electrolytic phases, while electrochemical polarization can be regarded as the deviation between the open circuit potential of the cell and the operating potential [27].

3.1. The dependence of battery performance on temperature

Lithium-ion batteries work optimally within the designed parameters only over a well-established temperature range. Thus, [33] it mentions that the temperature range is usually intended to be between 25 °C and 35 °C, as temperatures that are too high or too low can reduce the efficiency of the battery. In [34] it is specified that the reliable operating temperatures of lithium-ion batteries are in the range of -20 to 55 °C during discharge and 0 to -45 °C during charging. Typically, lithium-ion batteries work optimally in the temperature range of 20 °C to 45 °C [35].

3.2. Results of the of the cylindrical Li-ion battery pack thermal simulation

For this study, the commercial cylindrical lithium-ion battery, type 18650, minimum capacity 1950 mAh, maximum capacity 2200 mAh, nominal voltage 3.7 V, maximum charging voltage 4.2 V, dimensions 18×65 mm, manufactured outside the European Union. The 3S7P battery pack is assembled by the authors as part of this research.

Table 1 presents the parameters of the 18560 cylindrical li-ion battery used for thermal simulation [29], [36].

Table 1. Parameters of 18560 cylindrical li-ion battery used for thermal simulation [29], [36].

Parameter Description	Value	U.M.
Thickness of battery canister, $dcan$	0.25	mm
Battery radius, rB	9	mm
Battery height, hB	65	mm
Mandrel radius, rm	2	mm
Length of negative electrode, lnE	55	μm
Length of separator, ls	30	μm
Length of positive electrode, lpE	55	μm
Negative current collector thickness, $lnCC$	7	um
Positive current collector thickness, $lpCC$	10	um
Positive electrode thermal conductivity, kT_p	1.58	W/(m·K)
Negative electrode thermal conductivity, kT_n	1.04	W/(m·K)
Positive current collector thermal conductivity, kT_pCC	170	W/(m·K)
Negative current collector thermal conductivity, kT_nCC	398	W/(m·K)
Separator thermal conductivity, kT_s	0.344	W/(m·K)
Positive electrode density, rho_p	2328.5	kg/m3
Negative electrode density, rho_n	1347.33	kg/m3
Positive current collector density, rho_pCC	2770	kg/ m3
Negative current collector density, rho_nCC	8933	kg/ m3
Separator density, rho_s	1008.98	kg/ m3
Positive electrode heat capacity, Cpp	1269.21	J/(kg·K)
Negative electrode heat capacity, Cpn	1437.4	J/(kg·K)
Positive current collector heat capacity, $CppCC$	875	J/(kg·K)
Negative current collector heat capacity, $CpnCC$	385	J/(kg·K)
Separator heat capacity, Cps	1978.16	J/(kg·K)
Cycle time, tc	600	s
Inlet temperature, Tin	298.15	K
Cell capacity, QB	1.258	A·h
Ohmic overpotential at 1C, $\zeta 1C$	4.5	mV
Dimensionless charge exchange current, $J0$	0.85	
Diffusion time constant, τ	1000	s

Initial state-of-charge, $SOCi$	0.2	
Applied current, Iapp	2.5	A
The rate of discharge/charge, Cr	1	
Time of discharge, td	3600/Cr	s

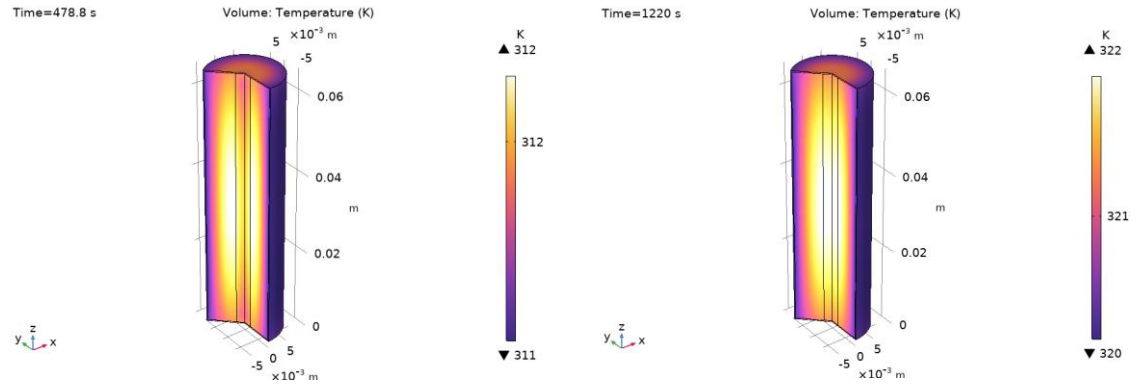
The specific sizes and values of the cylindrical lithium-ion battery used for modeling and simulating the thermal response, were used as input quantities for the COMSOL Multiphysics software environment, [36, 37].

The goal pursued by modeling and simulating the thermal response was to identify the way in which the temperature distribution is obtained, and to identify new solutions to obtain the heat dissipation. In order to simulate the distribution of the temperature generated inside a battery during the charging/discharging process, in a first step, the thermal behavior for a single battery was modeled. In this regard, ohmic heat, reaction heat, and polarization heat were considered.

The simulation model consisted of a *1D model* (which models the chemistry of the battery cell) and a *3D model* (modeling the temperature in the battery), which were coupled in the simulation process. The cell model was created using the Lumped Battery interface [35], for which the battery capacity and its initial state of charge were used. To identify the place of heat generation inside the cell, the *1D* model was used, and the 3D model was used to model the temperature profile of the battery cell [36].

The simulations performed in the paper [36], present the thermal behavior of the 18650 cylindrical battery at a charge/discharge current with a rate of 7.5C, where at t=1220 s, the temperature differences present the values: ΔTmax=23.775K, ΔTmean=22.917K, ΔTmin=22.039K.

For our research, we are interested in the thermal behavior of both the 18650 cylindrical battery and the 3S7P package, but at a charge/discharge current with a rate of 5.5C. This reasoning takes into account the fact that, in general, light two-wheeled vehicles have a less severe operating regime, as they are used in cities on routes without large slopes. In this context, we will choose the peak temperature value that occurs at t=1220 s, according to the research in [36], respectively an intermediate, random variant of t=478.8 s.



(a) (b)

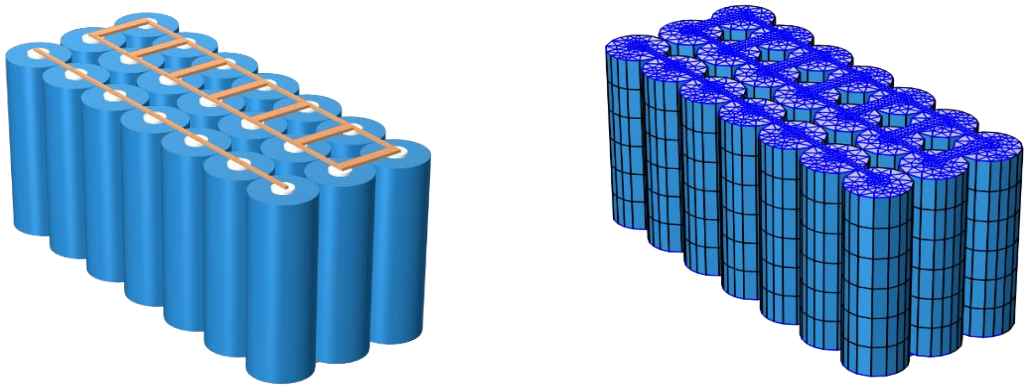
Figure 1. Temperature distribution in the battery at: (a) t1=478.8 s; (b) t2=1220 s

In order to have a comparative image of the temperature evolution inside the cylindrical lithium-ion battery, at different times of the charging process, *t1* = 478.8 s and *t2* = 1220 s, respectively, are considered. Figure 1,(a) shows the simulation of the temperature at *t1*=478.8 s, where it is observed that

the maximum temperature in the center of the battery, which is in the active material, has a value of 312 K, while on the outside of it, the temperature reaches the minimum of 311 K. In fig. 1(b), at *t2*=1220 s, the simulation of the temperature inside the battery is presented, where it is observed that the maximum temperature value in the center of the battery is 322 K (while the minimum temperature is 320 K).

In the next step, a battery array consisting of 3 cells linked in series with 7 cells linked in parallel (3S7P) is considered, thus forming a battery pack that will be subjected to this study. For the simulation of the thermal behavior of the battery pack 3S7P, the thermal conductivity, density, heat capacity and heat source in the battery are configured keeping the same values as in the case of thermal modeling of a cylindrical lithium-ion battery in the 2D/3D model, from the previous step [36, 37].

The 3S7P battery array features a straight stack/pack with series and parallel electrical links made of metal strips at the top and bottom, respectively, according to the 3S7P configuration. These metal bonds are included in the heat transfer model. The initial temperature of the battery is considered to be 298.15 K.



(a) (b)

Figure 2. Geometric structure of the 3S7P battery pack: (a) geometry display; (b) geometry mesh

Figure 2(a) shows the geometric structure of the battery pack to be modeled, and fig. 2(b), a tetrahedral lattice representation resulting from the addition and construction of a tetrahedral node specific to cylindrical lithium-ion batteries. Among the characteristic of this tetrahedral networks we can mention: mesh vertices – 12629 (value); tetrahedral – 29092 (value); prisms – 10620 (value), triangles – 17808 (value).

Figure 3 shows the simulation results regarding the thermal distribution of the 3S7P battery pack, at t = 523.62 s (0.14545 hours). The period taken for analysis is limited by the fact that the proposed system is designed to load and unload all the time. Or, either to discharge almost completely, after that, a charge. The thermal simulation does not aim to achieve a permanent regime of the temperature of the battery pack; it proposes to analyze its thermal behavior when a critical point is reached. Depending on the charge/discharge rate C of the electricity stored in them, the temperature rises more slowly or increases very quickly, depending on this parameter. The higher the charge/discharge cycle C, the higher the electricity consumption in the batteries; therefore, it discharges faster over time, and the temperature of the pack increases a lot.

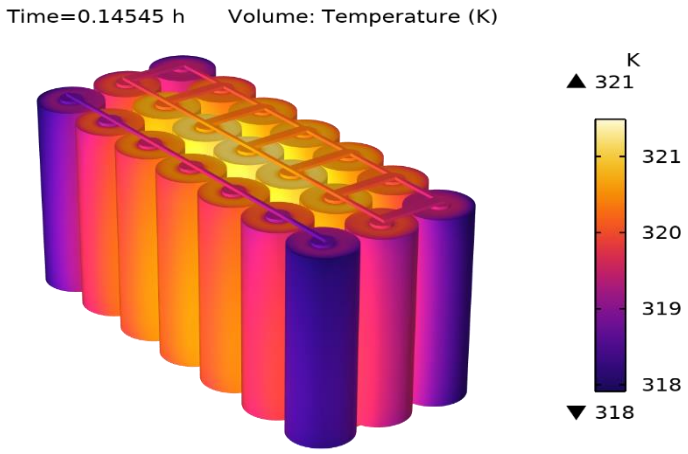


Figure 3. Thermal distribution in the 3S7P battery pack

In the case of the proposed simulation, a charge/discharge rate of 5.5C was considered, where it is observed that in its center, the maximum temperature is 321 K, and towards the outer parts of the battery pack, the minimum temperature is 318 K (the temperature difference between the inner and outer parts of the battery pack is 4 K). At a first approximation, we can consider that the cells in the middle of the battery pack become vulnerable to their thermal packaging. These are the elements that require thermal optimization in operation, which can be achieved through forced cooling or natural air cooling, but which would imply an increase in the dimensions of the battery pack. Or a larger battery pack positioning space, which is provided with slits to direct air currents in the case of natural cooling, or forced air cooling devices such as fans.

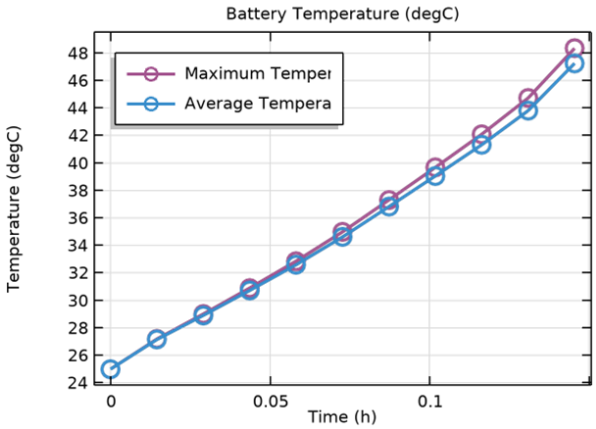


Figure 4. Battery pack temperature chart at charge/discharge cycles with the value of 5.5C

Figure 4 shows the graph of the maximum and average temperatures of the battery pack at t= 523.62 s (0.14545 hours) and charge/discharge cycle 5.5C, where it is observed that the initial temperature is 298.15 K (25 ^{o}C), the maximum temperature is 321.48 K (48.33 ^{o}C), and the average temperature is 320.39 K (47.24 ^{o}C).

For use, the battery pack can be placed in a plastic container (housing) with the dimensions: 150 mm long, 65 mm wide, 95 mm high, and 1.5 mm thick. A space of 1 mm has been provided between the cells of the battery matrix, respectively cells and the casing to allow the internal circulation of air

currents. The inside of the container is filled with air, and the battery cells are cooled by convection, but also by thermal radiation to the outside of the case.

Figure 5 shows the thermal distribution simulation of the 3S7P battery pack, at *t*= 523.62 s (0.14545 hours), at a rate of 5.5C, which was inserted into the protective housing. It can be seen that under the same conditions as the simulation in fig. 3, the maximum temperature increases by 1K, reaching 321 K.

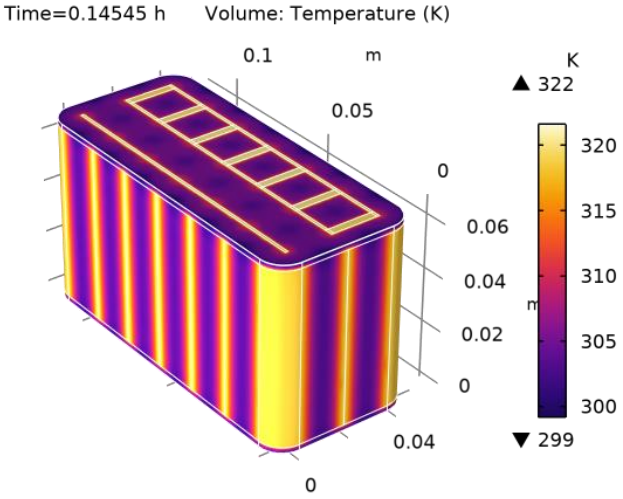


Figure 5. Thermal distribution of the 3S7P battery pack inserted into the protective case

Since the heat released by the cells of the battery pack is initially concentrated in the central part of the pack, it is found that, with time, this heat is taken up by the other cells in the battery array. Moreover, the cells that are close to the casing radiate heat to the casing material. The dark spaces (blue) represent the air spaces between the cells, respectively, the cells, and the protective case. The temperature of these has a minimum value of 299 K. The simulated model obtained highlights the temperature distribution over the entire pack of batteries that make up the block used to drive electric two-wheeled vehicles. The thermal analysis highlights the fact that stacking the batteries in compact blocks coordinates the temperature that has risen in the center of the created block. This temperature distribution indicates that the operating temperature of the batteries can be lowered if solutions to lower the temperature are identified in the middle of the created block.

Due to the standard dimensions imposed by the use of battery packs specific to two-wheeled electric vehicles, it is not possible to intervene in increasing the volume inside the case. In this context, the placement of the batteries in the case raises the operating temperature, which leads to limiting their performance. From the simulated models, solutions were identified to reduce the operating temperature through external forced cooling actions, which involved additional energy consumption. From the simulations performed, it can be seen that, compared to the cells located towards the end of the package (3S7P), the cells positioned in its center are the most vulnerable to excess heat during the loading/discharging process. Thus, in the center of the package results a temperature of 321 K results, while on its corners, the temperature reaches 318 K. When the battery pack is inserted into the protective case, all batteries become vulnerable, including those in the corners of the case. Already after a time of 0.14545 hours, their temperature reaches 322 K. However, it is noted that there is also a minimum temperature of 299 K, which represents the temperature in the air space between the cells and cells and the protective case.

4. Conclusions

For the battery cells to operate at the prescribed temperatures, it is necessary to identify the optimal operating temperatures of the battery pack (cells), to reduced excess temperatures, to prevent thermal evaporation, but also to ensure optimal charge/discharge cycles by balancing the charging voltage/current on each cell. It is also important to identify vulnerable cells, which, as observed from simulations, are found in the center of the battery pack, and to ensure a concentrated cooling process. Moreover, placing the batteries in closed protective housings causes the entire battery pack to overheat, as heat evacuation becomes very difficult. The simulations also result in a local heating of the protective case given by the batteries placed on its edge. This research aims to translate into an optimized physical model of battery pack used for the propulsion of electric 2-wheeled vehicles, which has a lower operating temperature than currently known models. Future research aims to validate the simulated models by developing an experimental stand that highlights the temperature distribution.

The COMSOL Multiphysics software offers capabilities for simulating and analyzing thermal processes, particularly in modeling thermoelectric effects. This includes assessing permissible currents and the thermal stresses induced by nominal currents. In battery packs, thermal stresses arise from the electrocaloric effect caused by the current flow. Consequently, it is recommended to monitor these stresses through simulation and to compare the numerical results with the maximum allowable temperature to validate them. A thorough understanding of the battery pack's design components and installation conditions allows for validated simulation results, facilitating the identification of practical solutions to optimize thermal losses.

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Nomenclature

Bi - the dimensionless number Biot
C - battery charge/discharge rate
Cp - specific heat capacity, [J/kgK]
Lc - characteristic length, [m]
h - heat transfer coefficient, [W/m^{2}K]
k - thermal material conductivity [W/mK]
$k_{T,i}$ – the thermal conductivities of the materials of which the battery layers are made, [W/mK]
k_a - thermal conductivity in the longitudinal direction, [W/mK]
k_r - thermal conductivity in the radial direction, [W/mK]
k_r, k_a, k_z - thermal conductivities of the battery cell in the x, y and z directions respectively, [W/mK]
L_i - the thicknesses of the different layers of the cell, [m]
$\dot{\boldsymbol{Q}}$ - volumetric heat generation rate for the battery cell, [W]
r – battery cell radius, [m]
T – absolute temperature, [K]
t – time, [s]
T_{amb} - absolute temperature under ambient conditions, [K]
V_i - the volume of each component in the battery structure, [m3]
ρ - the density of the active material of the cell, [kg/m3]

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