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Article

Study of cooling system performance on lithium-ion batteries for an electric vehicle

Estudio del desempeño de un sistema de enfriamiento en baterías de iones de litio para un vehículo eléctrico

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Abstract

The acquisition of electric vehicles has grown considerably, as a result, autonomy and safety became an opportunity for improvement, one of the main systems that involve autonomy and safety are batteries. The safety and the performance of the batteries are directly related to the temperature reached during charge and discharge operation. In this paper, a CFD study is carried out on the thermal and hydrodynamic performance of a cooling system used to prevent overheating of lithium-ion batteries used in electric vehicles. Air as cooling fluid is used, which is directed towards the battery cells to remove the heat generated by each of these cells. An in-line arrangement for the batteries is analyzed, different velocities and discharge rate to obtain temperature profiles on the cell surface are used, as well a total pressure drop along the cell array. The minimum inlet velocity which the working fluid must work to ensure adequate temperature of the battery cells in operation is found.

Objective	Methodology	Contributions
Thermal and hydrodynamic performance study.	Geometric configuration.	Results analysis
Battery temperature control.	Computational model.	Cooling system configuration.
	Model solution and validation.	

Lithium-ion battery, CFD, Cooling system

Resumen

La adquisición de automóviles eléctricos ha crecido considerablemente, esto ha traído consigo algunas necesidades en el área de seguridad y autonomía del automóvil eléctrico, uno de los principales sistemas que involucra ambos temas son las baterías, ya que la seguridad y sobre todo su rendimiento está relacionado directamente con la temperatura que alcanzan durante su funcionamiento de carga y descarga. En el presente trabajo se realiza un estudio usando CFD del desempeño térmico e hidrodinámico de un sistema de enfriamiento, usado para evitar el sobrecalentamiento de las baterías de iones de litio usadas en los vehículos eléctricos. Se utiliza aire como fluido de enfriamiento, el cual es direccionado hacia las celdas de la batería para remover el calor generado por cada una de estas celdas. Se analiza un arreglo en línea para las celdas de la batería, se utilizan diferentes velocidades y diferentes razones de descarga, para obtener los perfiles de temperatura sobre las superficies de las celdas, así como también la caída de presión total a lo largo del arreglo de las celdas. Se encuentra la velocidad mínima a la cual debe trabajar el fluido de enfriamiento para garantizar una adecuada temperatura de las celdas de la batería en operación.

Objetivo	Metodología	Contribuciones
Estudio del desempeño térmico e hidrodinámico.	Configuración geométrica.	Análisis de resultados.
Control de temperatura de baterías.	Modelo computacional.	Configuración de sistema de enfriamiento.
	Solución y validación del modelo.	

Batería de iones de litio, CFD, Sistema de enfriamiento

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Introduction

Global warming, which impacts the planet worldwide, is one of the main problems that must be tackled with immediate and concrete actions. In order to implement actions to mitigate climate change, a large amount of resources have been allocated to study its causes and effects. It is known that one of the main causes of climate change is the emission of greenhouse gases, where one of the main sources of these gases is the transport industry, specifically the automotive industry, which mainly uses internal combustion engines (L. Li et al., 2018), which use fossil fuels as their main source of energy. One of the actions that have been implemented is the replacement of internal combustion engines with electric motors, which represents a benefit in reducing greenhouse gas emissions (Shi et al., 2019). With the advancement of technology, the use of electric motors instead of internal combustion engines has increased in recent decades, especially in compact cars and motorbikes that do not require high power to operate.

With the use of electric motors in automobiles, different problems and challenges have arisen that must be addressed, one of the main problems has to do with the batteries used for the operation of the electric motor, these batteries must work properly and under certain operating conditions, which have a direct impact on the performance of the batteries during their charging and discharging operation. It is for this reason that during this operating cycle, the heat generated must be regulated, as this heat reduces the performance of the battery, also affecting the safety and useful life of the battery.

Due to the above, it is necessary to have a cooling system for the battery used in electric or hybrid vehicles. One of the batteries commonly used is the lithium-ion battery, which must be kept at an operating temperature range between 15-40 °C (288-313 K), working within this range avoids performance problems and above all safety problems, since if any of the battery cells explode there can be serious consequences for the crew.

In recent years, cooling systems have been used for batteries, these systems use air as the cooling fluid and the heat transfer mechanism by natural or forced convection.

Box 1

Figure 1
Lithium-ion cell

Source: *Own elaboration.*

The battery is composed of several cells, which are arranged according to the current and voltage requirements of the engine, in Figure 1 shows a lithium-ion cell, an arrangement of these cells makes up what is the battery..

Box 2

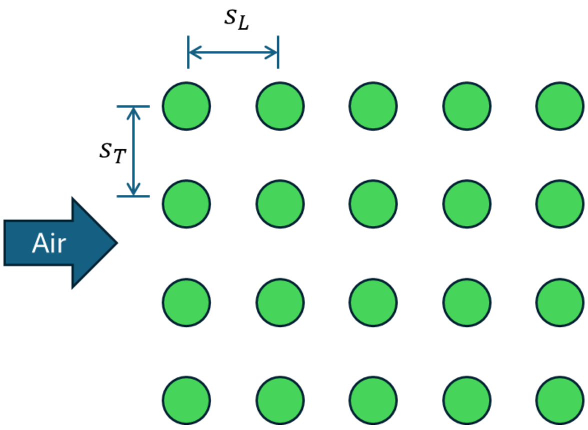

Figura 2
Cell arrangement for the battery.

Source: Own elaboration.

A type of arrangement is used in the battery configuration to place the different cells, which arrangement must contain certain spaces to ensure air circulation through the battery cells. Usually the in-line arrangement is used which is shown in Figure 2. It can be seen that one of the important parameters is the transverse distance () and the longitudinal distance (). There may be another arrangement known as staggered arrangement, for the purpose of this study only the in-line arrangement is considered for analysis.

The design of the cooling system of a battery is crucial for its correct operation, its sizing must be configured to the use of the vehicle and the behaviour of the battery charging and discharging. Therefore, in this paper, a cooling system is analysed to ensure that the battery to be used in a motorbike works in a suitable temperature range.

Background

Nowadays the sale of electric vehicles has increased worldwide, due to this, areas of opportunity for improvement have been identified in the different systems that integrate an electric vehicle, one of the main systems that have been identified as possible improvements is the cooling system of the batteries, because the batteries can present an excessive heating during its operation cycle, some solutions have been implemented to remove the heat that is generated with the work of the batteries, since the increase of the temperature can affect the performance and the useful life of these.

The heat generated during the operation of batteries in electric vehicles significantly raises the temperature of the batteries, which directly affects the performance of the battery, especially if it is not maintained within a certain operating range, also the presence of high temperatures generates problems in safety and affects the life of the battery, it can also cause a thermal leakage, which represents a potential danger, which is why the heat generated has been identified as one of the main causes of increased operating costs of electric and hybrid vehicles.

In this paper, they focus on the development of a cooling system specifically designed for lithium-ion batteries, widely used in the automotive industry, the main proposal of their work consists of three cooling strategies, the first one is air cooling, the second one is liquid cooling and the third one is a flat heat pipe system. These strategies offer complementary solutions for battery heat dissipation. They conducted their thermal analysis of the battery, which allowed them to identify the critical areas where the most heat is generated during operation. This analysis allows them to maximise heat dissipation by focusing on cooling these identified regions. To evaluate their proposals, they use fluid dynamics models (CFD) validated with the surface temperature of the cells that make up the batteries.

Their results report that the flat heat pipe approach provides up to 42.7% better cooling during discharge. As expected, the liquid cooling system and the heat pipe show better performance compared to natural air cooling.

Achieving a mathematical model of an efficient design of a cooling system for batteries used in electric vehicles is not straightforward, because several variables must be considered at the same time, which generates a multi-objective optimisation problem. they present a mathematical model for a battery cooling system, in their model they consider air as a cooling fluid and fins for better heat dissipation. The aim of their research is to reduce three key parameters in heat dissipation in lithium-ion batteries: the average temperature, the standard deviation of the battery temperature and the pressure drop of the cooling system. Minimising the average temperature ensures that the battery operates within a safe range and thus avoids overheating. When the standard deviation is minimised, a uniform temperature distribution is achieved throughout the battery, thus avoiding hot spots that could cause thermal runaway. Finally, decreasing the pressure drop helps to improve the pressure drop in the cooling system, thus requiring less energy to maintain the battery temperature within the desired range. As results, they report the optimised parameters of the cooling system, which presents a balance between cooling efficiency, system volume and energy consumption.

Similarly, they propose a mathematical model designed to improve the accuracy of the data obtained by numerical analysis of the temperature inside the battery cells. The above aims to realise a proper design of a battery cell that leads to an increase in the lifetime of the battery cells and the energy efficiency of the electric vehicle under the specific traffic operating conditions. By comparing their results they obtain that the use of the proposed mathematical model provides more accurate calculations of the local thermal performance of the air-cooling system, with a direct influence on the optimisation of its design and construction.

Several researches have taken into account the thermal analysis during high current demand charging and discharging.

Zúñiga-Cerroblanco, José Luis, Conejo-Chavando, Luis Daniel, Huerta-Gámez, Héctor and Pérez-Gárcia, Víctor Lauro. [2024]. Study of cooling system performance on lithium-ion batteries for an electric vehicle. Journal of Technological Development. 8[21]-1-10: e3082110.
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They construct an air cooling system based on heat pipes to control the temperature of the lithium-ion (Li-ion) battery cell and module for a high current discharge rate (184 A). They perform an analysis of the cell temperature experimentally and numerically, evaluating different cooling strategies, such as natural convection, forced convection and evaporative cooling. According to the experimental results, natural convection reduces the average cell temperature by 6.2%, however, forced convection, which uses air as the cooling fluid, is significantly more effective, reaching up to 33.7% in reducing the average cell temperature. The results of the simulations are validated with the experimental results for natural and forced convection. The evaporative cooling method improves the cooling system, it is shown to be the most effective strategy, reducing the maximum cell temperature by 35.8 %, while for the full battery the reduction is 23.8 %. This reduction is due to the high heat transfer coefficient associated with evaporation.

In electric vehicles the robustness of each of the systems must be taken care of, in the case of electric vehicles special attention must be paid to the battery system and the cooling system of these batteries. Therefore, they propose 4 novel cooling system designs based on liquid-cooled plates, which flow through microchannels to improve the dissipation of heat generated by the batteries. They consider a 35 V battery composed of 12 LiFePO4 type cells connected in series. The proposed designs are evaluated and compared using various criteria, such as discharge rate, thermal contact resistance and external short-circuit. In the results of their study they identify the most efficient design, which achieves the best cooling with the lowest energy consumption during discharge. This design achieves a maximum temperature of 30°C, with a maximum temperature difference of less than 5°C between cells, which is important to ensure a homogeneous temperature and prevent hot spots. As for the thermal contact resistance, the results do not show a significant effect for each of the designs. They report that care must be taken in the selection of the coolant flow rate, which must be adequate, as this parameter is key to maintain the maximum temperature and the temperature gradient in the battery, an inefficient flow rate could cause overheating of the cells.

In relation to the arrangement of the battery cells, they present a proposal for a cooling system, which is based on countercurrent air for a staggered configuration, this proposal seeks to improve the low heat transfer efficiency of the air cooling module in the lithium-ion battery, as well as to reduce the temperature difference between the cells. In their results they identify and analyse the main factors affecting the temperature distribution inside the cell. Their results show that both the maximum temperature and the temperature difference of the battery gradually decreased with increasing flow channel height. As expected, the higher the channel height, the higher the flow rate of the cooling fluid and consequently the higher the heat dissipation capacity. The number of flow channels had a negligible effect on the reduction of the maximum coil temperature. The optimal parameters identified in their research were: channel height of 4 mm, flow velocity of 3 m/s and a total of 6 channels. With this configuration, the cooling system achieved a better temperature distribution, which ensures a more efficient and safer operation.

Geometric model

A typical arrangement of the lithium-ion cells that make up a battery is shown in Figure 3 below.

Box 3

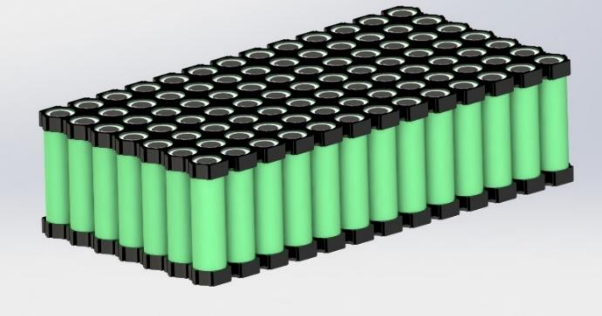

Figure 3

Cell arrangement for the battery.

Source: Own elaboration.

Zúñiga-Cerroblanco, José Luis, Conejo-Chavando, Luis Daniel, Huerta-Gámez, Héctor and Pérez-Gárcia, Víctor Lauro. [2024]. Study of cooling system performance on lithium-ion batteries for an electric vehicle. Journal of Technological Development. 8[21]-1-10: e3082110.
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Box 4

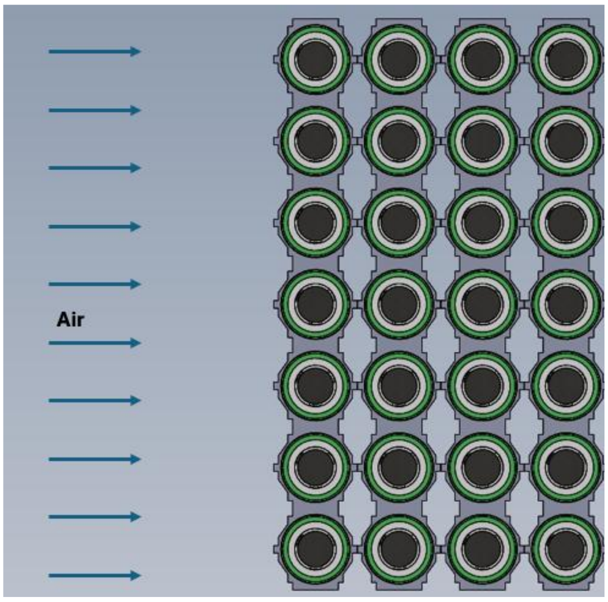

Figure 4
Cell arrangement for the battery, top view
Source: Own elaboration.

Figure 4 shows a partial view of the in-line arrangement of each of the cells that make up the battery, this arrangement presents both vertical and horizontal alignment of the different cells, this causes the cooling air to flow through the cells, completely surrounding them with the cooling fluid, which will help the air to remove the heat generated by each of the cells.

The battery built to run the motorbike must provide enough power to run a 72 Volt, 3000 W Kunray engine. The cells used for the construction of the battery are a 3.7-4.2 Volt rechargeable cell, with a capacity of 9800mAh of Lithium Ion material.

The dimensions of one of the cells that make up the battery are shown in Figure 5, it has a diameter of 19 millimetres and a height of 65 millimetres. The in-line array has the dimensions shown, a longitudinal and transverse distance of 20 millimetres, the array is composed of 10 cells wide by 20 cells long.

Box 5

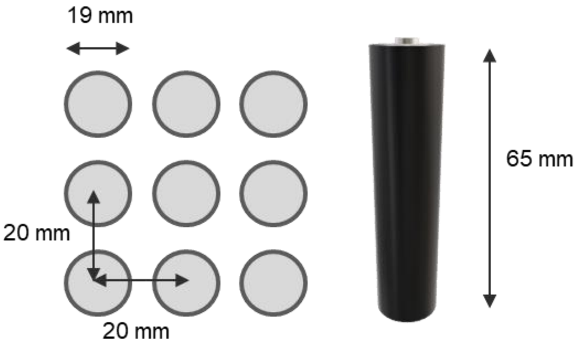

Figure 5
Cell and battery array dimensions
Source: Own elaboration.

Figures 6 and 7 present the battery constructed to operate the engine.

With this arrangement the 72 volt motor can be driven, which requires a battery consisting of 20 cells connected in series and 20 cells connected in parallel, plus the battery provides power for a DC-DC voltage converter from 72 Volts to 12 Volts. This converter in turn powers the accessories such as the headlights, stop lights, turn signals, the BMS display and the digital speedometer.

The weight of the battery is 16 kilograms, which is less than the weight of some commercial batteries, which is up to 20 kilograms. The performance parameters of the battery are as follows, nominal voltage of 3.7 Volts, nominal capacity of 9800 mAh, equivalent density of 2018 kg/m^3, volume of $1.654\ x\ 10^{-5} m^3$.

Box 6

Figure 6
Constructed arrangement of cells for the battery
Source: Own elaboration.

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Box 7

Figure 7

Battery built by cells.

Source: Own elaboration.

Methodology and materials

Once the geometry of the battery cell arrangement is built in CAD, the model is exported to ICEM ANSYS, where the mesh required for the CFD analysis is created. Figure 8 shows the computational domain generated, taking as boundary conditions an input velocity and as an output condition an output pressure, as well as the symmetry condition, this will reduce the number of elements and therefore save computational time required for the solution.

Box 8

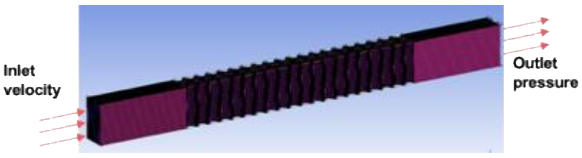

Figure 8

Computational domain built

Source: Own elaboration.

Box 9

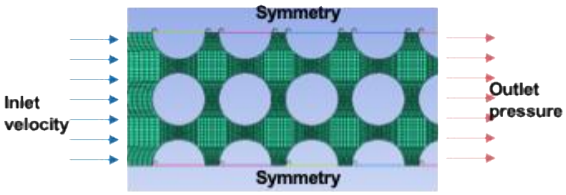

Figura 9

Mesh constructed in the computational domain and boundary conditions assigned

Source: Own elaboration.

Box 10

Table 1

Mesh independence study.

Mesh elements	$\boldsymbol{T}\ [\boldsymbol{K}]$	$\dfrac{\Delta \boldsymbol{T}^{i} - \Delta \boldsymbol{T}^{i+1}}{\Delta \boldsymbol{T}^{i}}$
668,945	307.605	$5.468\text{x}x10^{-3}$
1,105,188	307.512	$1.8574\text{x}x10^{-4}$
1,387,097	307.510	-----------
1,507,474	307.510	-----------

Source: Own elaboration

Figure 9 shows the boundary conditions used for the computational analysis; there is an input velocity, an output pressure and the symmetry condition is assigned to simplify the computational model. It is also possible to appreciate the mesh built on the computational domain, a mesh dependence analysis is performed, for which the temperature variable is monitored for different numbers of elements of the generated mesh, Table 1 shows temperature variation as a function of the number of elements used in the model. It is observed that, from 1,105,188 elements, there is no longer a significant variation in the temperature, this indicates that using a mesh with a higher number of elements than indicated will not improve the accuracy of the analysis, but it will require a higher computational capacity. It is for this reason that the indicated mesh is considered suitable for computational analysis as it has a balance between accuracy and computational efficiency.

In the analysis, air is used as the cooling fluid, for which a density of $1.225\ kg/m^3$, un specific heat of $1006.43\ J/kgK$, a thermal conductivity of $0.0242\ W/mK$ and a viscosity of$1.7894\ x\ 10^{-5} kg/ms$.

For the analysis a volumetric heat generation per cell is considered as shown in Table 2, three different scenarios will be analysed, each at different discharge rates of the battery, for which it is assumed that it is discharged at a rate of 1C, 2C and 3C. According to the demand required by the motorbike, the discharge ratios are estimated to be 1C and 2C, the discharge ratio of 3C is when the battery is already used in a car, as a higher power is required.

Box 11

Table 2

Volumetric heat generated by battery cells for different discharge ratios.

Reason for discharge	Volumetric heat generation
1C	5318 W/m^3
2C	19,452 W/m^3
3C	42,400 W/m^3

Source: Own elaboration

The governing equations to be solved are presented below.

For the solid, we have the energy equation, equation (1):

$$\rho C\frac{\partial T}{\partial t}=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial x^2}\right)+\dot{Q} \qquad (1)$$

In the above equation, ρ is the density, C is the specific heat, T is the battery temperature, k is the thermal conductivity and Q˙ in volumetric heat generation.

For the fluid we have equation (2), which is the energy equation, equation (3) is the continuity equation and equation (4) is the momentum equation..

$$\rho_f C_f\frac{\partial T_f}{\partial t}+\nabla\left(\rho_f C_f \vec{v} T_f\right)=\nabla\left(k_f \nabla T_f\right) \qquad (2)$$

$$\nabla(\vec{v})=0 \qquad (3)$$

$$\rho_f\left[\frac{\partial \vec{v}}{\partial t}+(\vec{v}\nabla\vec{v})\right]=-\nabla P+\mu\nabla^2\vec{v} \qquad (4)$$

In the above equations, ρ_f is the density of the fluid, C_f is the specific heat of the fluid, T_f is the temperature of the fluid, k_f is the thermal conductivity of fluid, μ is the dynamic viscosity of the fluid and $\vec{v}$ is the flow rate of the fluid.

For the analysis, air velocities from 0.1 m/s to 1 m/s are considered, this for each of the volumetric heat generated according to the discharge ratio, the assigned outlet pressure is 0 Pa. The coupling between the solid and the fluid is considered and the walls are taken as no slip, the turbulence model taken is the (Renormalisation Group). The time step of 1 second is considered, where the number of iterations for each time step is 50.

Results

The results obtained from the analysis are presented below, showing the temperature contours for each of the study cases, the maximum temperature reached and the total pressure drop across the battery for each case.

Box 12

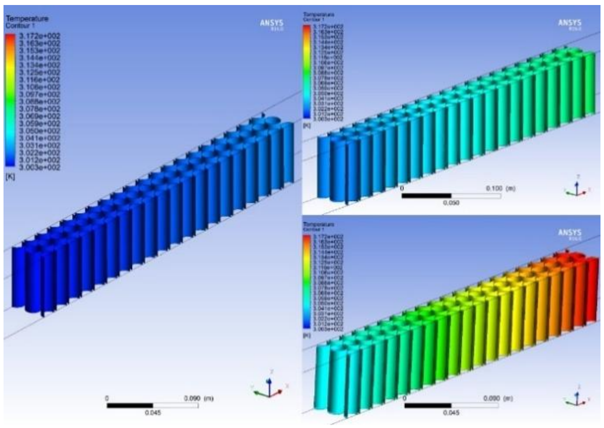

Figure 10

Temperature contours for an inlet velocity of 0.5 m/s and for a discharge rate of 1C, 2C y 3C.

Source: Own elaboration.

Figure 10 shows the temperature contours of the battery array for an analysis speed of 0.5 m/s for the different discharge ratios analysed. It is observed that the maximum temperature reached is 302.19 K, 308.02 K and 317.32 K for a discharge rate of 1C, 2C and 3C, respectively.

The temperature contours for a plane through the battery cells and the cooling fluid are shown in Figure 11, for a speed of 0.5 m/s and a discharge rate of 3C, the temperature of the battery cells and also the temperature of the fluid can be observed, it can be seen how the fluid enters at a temperature of 300 K and increases as it removes the heat produced by the battery cells until it exits the battery and has a temperature of 315 K.

Box 13

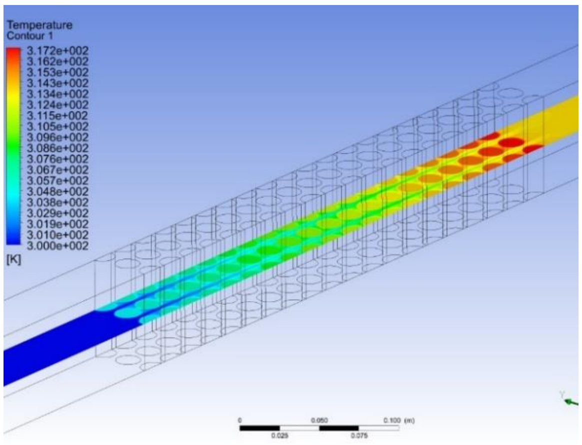

Figure 11

Temperature contour for battery cells and fluid.

Source: Own elaboration.

Figure 12 shows the maximum temperature that can be reached in the final section of the battery for speeds of 1, 0.5 0.3 and 0.1 m/s, for the battery discharge ratios of 1C, 2C and 3C. From the graph it is deduced that for the discharge rate of 1C the temperature of 313 K is not exceeded, remembering that working above this temperature affects the performance, safety and useful life of the battery; for the discharge rate of 2C it is found that when the speed is 0.1 m/s the temperature of 313 K is exceeded, therefore it is recommended that for this discharge rate the cooling fluid has a speed greater than 0.1 m/s. Finally, for the discharge rate of 3C it is deduced that the cooling fluid must work above 0.5 m/s, since below this speed, the maximum temperature reaches values up to 373.4 K.

Box 14

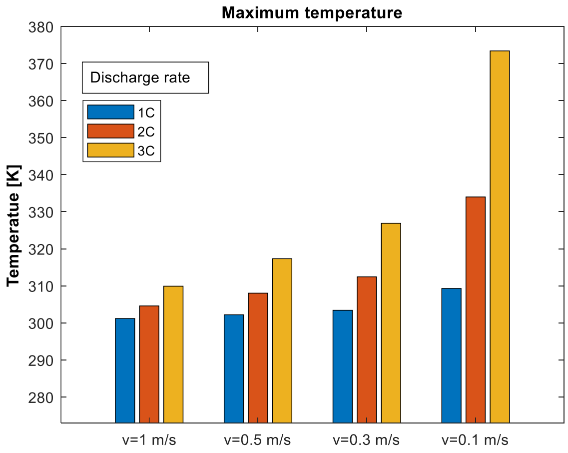

Figure 12

Maximum temperature reached by the battery for different discharge rates and ratios.

Source: Own elaboration.

Another variable of interest in the battery cooling system is the pressure required for the movement of the cooling fluid. Figure 13 shows the pressure contour of the fluid along the battery cell array for a velocity of 0.5 m/s, showing a maximum pressure of 22.9 Pa at the inlet of the cell array and decreasing as it moves out of the battery.

Box 15

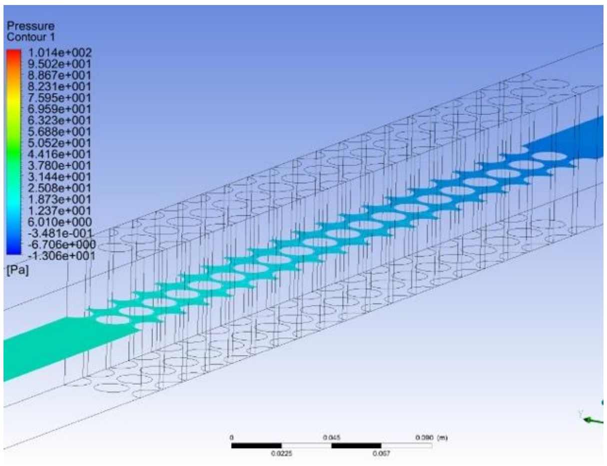

Figura 13

Fluid pressure contour through the coil for a velocity of 0.5 m/s.

Source: Own elaboration.

The fluid pressure along the battery for a speed of 0.3 m/s is shown in Figure 14, the behaviour is observed, it can be seen how the pressure decreases as the fluid enters the battery arrangement and how slight increases are observed each time the fluid collides with any of the cells of the battery.

Box 16

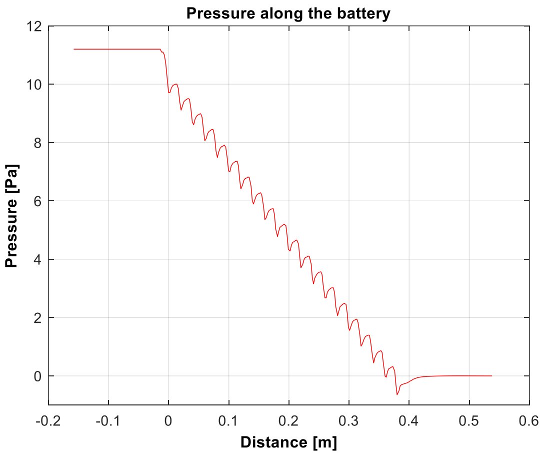

Figure 14

Fluid pressure contour through the coil for a velocity of 0.5 m/s

Source: Own elaboration.

Box 17

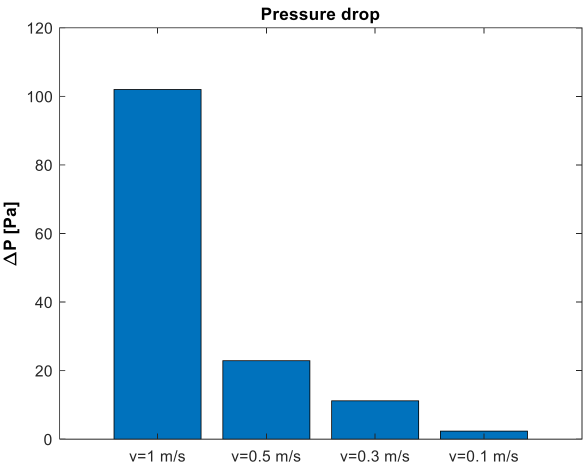

Figure 15

Fluid pressure contour through the coil for a velocity of 0.5 m/s

Source: Own elaboration

Figure 15 shows the pressure drop of the cooling fluid across the coil for the velocities of 1, 0.5, 0.3 and 0.1 m/s. As expected, the higher the velocity, the higher the pressure drop. As expected, the higher the speed, the higher the pressure drop, a considerable increase in the pressure drop from 0.5 m/s to 1 m/s is observed, so that the speed of 0.5 can be considered as the appropriate speed for the cooling fluid, since also at this speed the maximum temperature for a discharge rate of 2C is around the 313 K allowed.

Conclusions

In conclusion, a numerical model that simulates the cooling of the lithium-ion cells that make up the battery is available. The battery is analysed for different discharge ratios and different cooling fluid velocities. It is found that when the discharge ratio of the battery is 1C, the battery works within the temperature range suitable for its operation, when the discharge ratio is 2C the cooling fluid is required to have a minimum velocity of 0.3 m/s and for a discharge ratio of 3C a cooling fluid velocity above 0.5 m/s is required. The pressures and pressure drop across the coil arrangement are reported. It is found that for the cooling fluid to flow at a velocity of 0.5 m/s a pressure of 22.9 Pascals is required.

As future work, experimental tests will be carried out on the constructed battery, which will be installed on an electric motorbike, and the corresponding tests will be carried out. The experimental results will be compared with the numerical results.

The battery cooling solutions are considered to be temporary solutions, as the electric vehicle industry is working on and expecting a breakthrough in electric energy storage technology in terms of performance, lifetime, safety, specific energy and above all cost.

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Basics

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