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## Modelling Improved Solutions to Reduce the Temperature in Lithium-Ion Batteries



**Abstract:** - Lithium-Ion batteries are the most common energy storage devices used in electric vehicles. Battery heating management is a current topic, and modern solutions to reduce the temperature, as well as to avoid major or catastrophic defects. The 18650 model is often found in commercial models on the market. Using the the New European Driving Cycle (NEDC) standard that models the driver's behaviour with constant acceleration and braking, this work aimed to identify optimal battery cooling solutions on a Renault Zoe vehicle type. The two research directions focused on the variation of the cooling environment, respectively the variation of the positioning of the output/input plugs. The simulations were carried out in COMSOL Multiphysics starting from data provided by Model Advisor in MATLAB numeric computing environment.

**Keywords:** Lithium-Ion batteries, 3D modelling, temperature evaluation.

### I. INTRODUCTION

The gradual transition from fossil fuels to alternative energy sources leads to finding the most energy-efficient solutions for electric vehicles [1-4]. An essential component of such systems is represented by the electric energy storage solution (battery system). The most common solutions found in the automotive industry are represented by Li-Ion batteries (LIB's) [5, 6]. The major challenge that comes with these solutions is the avoidance of catastrophic situations of overheating or even explosion of these devices. To improve the safety achievements of LIBs, a performing battery thermal management system (BTMS) is required [7, 8]. An increase above the acceptable limits of the battery temperature can cause a series of defects that start from the discovery of the electrolyte, short-circuit, ceramic collapse and can even reach thermal runaway.

Thus, the current BTMS solutions are classified in passive BTMS, external active BTMS and internal active BTMS [7]. From the first category we find extinguishing systems that equip the battery. They can be furnished with smart sensors to downgrade either power interruption or temperature reduction devices. The research of the last decades worldwide has been harmonized with international standards [9, 10]. The most important advantage of this fire extinguishing thermal management system is its mature technology. For these systems it is easier to find the sensor technology and necessary fire extinguishing equipment in the market, and the price is low. External active solutions contain cooling systems either with air or with specific media refrigeration systems. A Phase Changing System, a Heat Pipe Cooling System or a Preheating System are also considered possible. The sequential or dislocated arrangement of the battery cells, as well as the number and placement of vents is a concern of these systems too [10-12]. Because a fireproof capsule package has no restrictions on the flame-retardant material a new methodology was opened for battery thermal management.

Internal Active BTMS consists of Thermal Management Through Controlling the Internal Reactions of the Battery. In this category we find Flame Retardant Additives (like Phosphorus-Based Flame Retardant, Nitrogen Flame-Retardant, Halogen-Based Flame Retardant) [13] and Capsule Flame-Retardant Package [14].

For thermal management through temperature control, the excess heat dissipated within the battery is computed by specific heat transfer methods. Most of the methodologies are mechanical, they are energy consuming because they require mechanical structures and dedicated space. Thermal management by controlling reactions inside cells is to be achieved through knowledge of electrochemistry and materials science. It is an ideal active safety system with excellent implementation and promptness and can even suppress battery thermal runaway before it occurs [15, 16]. Therefore, any non-invasive way of reducing the temperature inside the battery is welcome.

It is also important to follow the evolution of the battery temperature variation considering real, standardized operating cycles. In this sense, the developments and studies of the last decades have led to a series of driving cycles. Thus, The Worldwide harmonized Light vehicles Test Procedure (WLTP) [17] is a global driving cycle

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standard. This evaluates the levels of pollutants, CO<sub>2</sub> emission and fuel consumption of conventional internal combustion engine (ICE) and hybrid automobiles, as well as the all-electric range of plug-in electric vehicles. The New European Driving Cycle (NEDC) (last updated in 1997) [18] was a driving cycle, designed to assess the emission levels of car engines and fuel economy in passenger cars (which excludes light trucks and commercial vehicles). The NEDC is composed of two parts: ECE-15 (Urban Driving Cycle), repeated 4 times, is plotted from 0 s to 780 s; EUDC cycle is plotted from 780 s to 1180 s [19], like Fig. 1.

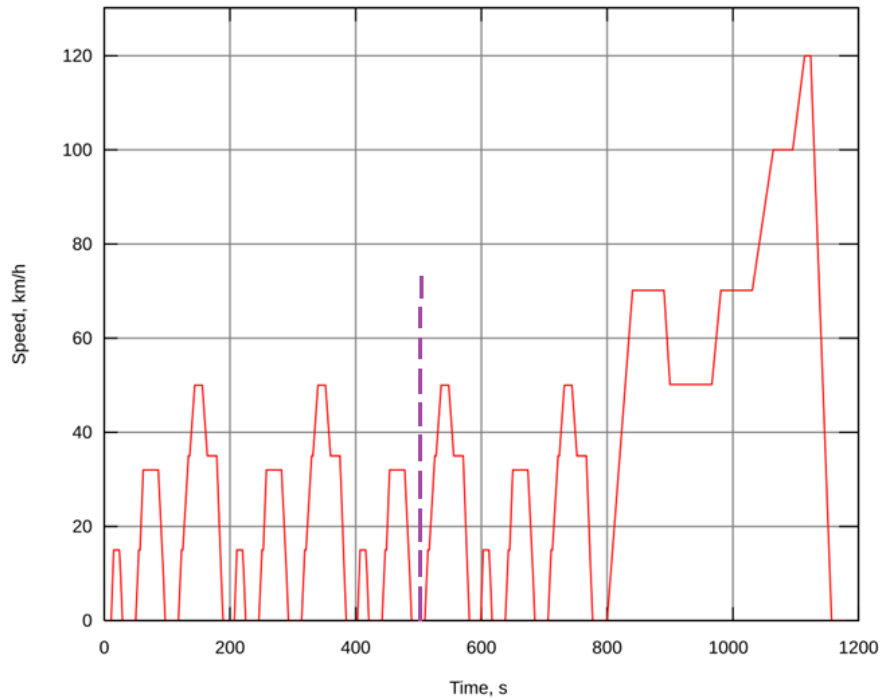


Fig. 1. The NEDC driving cycle according to [19] (the initial interval of 500 s used in the study is highlighted with a dashed purple line).

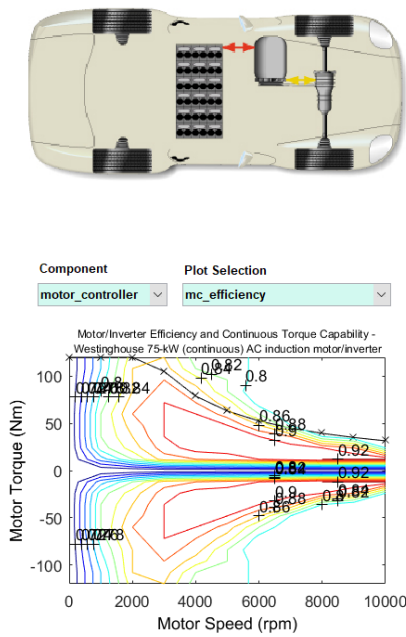
In this paper, a comparative study was carried out on an 18650-model battery considering various cooling media (air, freon, ethylene), using several solutions for the inlet and outlet sockets of the cooling agent. The case of a Zoe Renault car for which a NEDC type drive cycle was used constitutes an additional argument on the solidity of the conducted study.

## II. MATERIALS AND METHODS

To have the most accurate information regarding the battery current variation during a NEDC type driving cycle, the ADVISOR Tool Simulation program [20] was used. As one can notice Fig. 2 and Fig. 3 provides a series of essential data once the properties of the vehicle is introduced into the simulation model, and the drive path is selected. The results provided by the simulation is exported from MATLAB to MS Excel. The COMSOL model calculates the applied current by using an input variable of C-rate (Fig. 2). The current values imported from advisor are calculated into a vector of C-rates. This serves as the variable input of the COMSOL model (Fig. 3).

A previous work [21] studied the influence of some parameters such as the number and positioning of the cells in the battery (in line or honeycomb). Also, the distance between the cells was analysed. In this sense, the optimal solution was used in which 15 cells organized in the form of a honeycomb were considered (Fig. 4). The modeling was performed with the assistance of COMSOL Multiphysics software [22].

Vehicle Input



Component	version	type	max pwr (kW)	peak eff	mass (kg)
Vehicle	?	VEH_SMCAR			592
Fuel Converter	?	fc options			
Exhaust Aftertreat	?	EX_CI			
Energy Storage	rint	pb	26	321	286
Energy Storage 2	?	ess 2 options			
Motor	?	MC_AC75	33	0.92	40
Motor 2	?	motor 2 options			
Starter	?	starter options			
Generator	?	gc options			
Transmission	man	man		1	50
Transmission 2	?	trans 2 options			
Clutch/Torq. Conv.	?	clutch/torque converter ...			
Torque Coupling	?	TC_DUMMY			
Wheel/Axle	Crr	Crr			0
Accessory	Const	Const			
Acc Electrical	?	acc elec options			
Powertrain Control	ev	man			

Fig. 2. First page menu for ADVISOR Tool Simulation program [20].

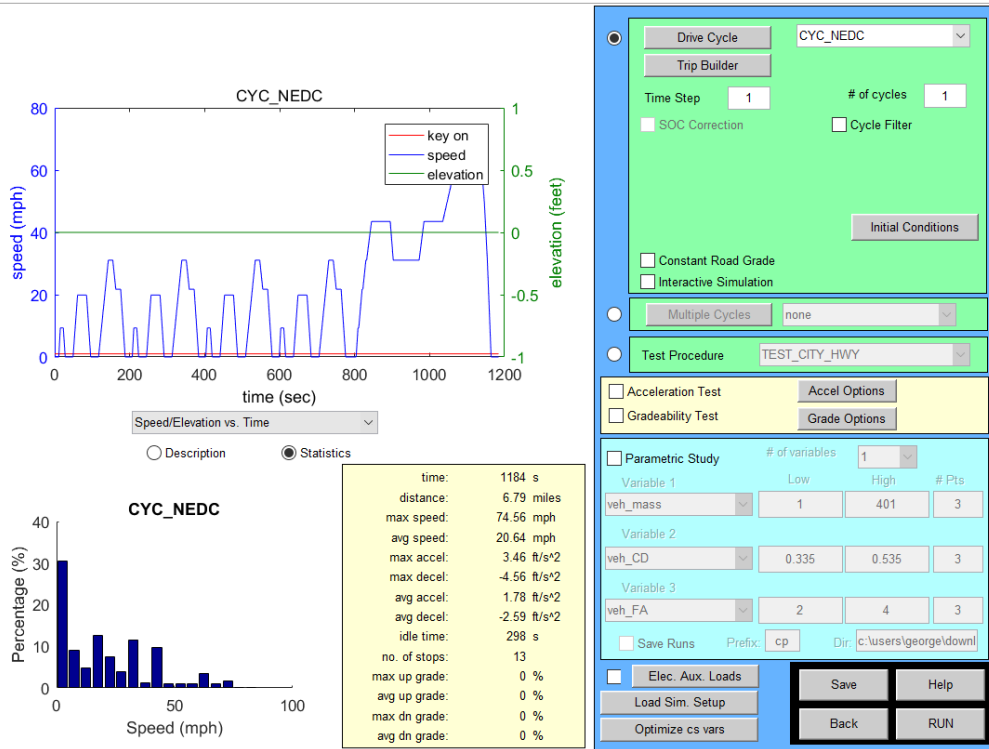


Fig. 3. Second page menu for ADVISOR Tool Simulation program [20].

In Fig. 4 you can also see the dimensions of the entire assembly: length = 180 mm, width = 81 mm and height = 68 mm. The model is built such that the individual cells are arranged in a matrix pattern within the cubical container to form the battery module. The 15-cell model has entry points for the coolant to enter the container to cool the cells and exit point/s where the coolant exits the container. Our simulations were performed using a 2.5 GHz CPU with 16 GB RAM. Due to this aspect, there were used only the first 500 s of the NEDC model (Fig. 1). In these conditions all proposed models have a range of 87606 to 91052 number of tetrahedra in the mesh and the average computational time is over 29 minutes.

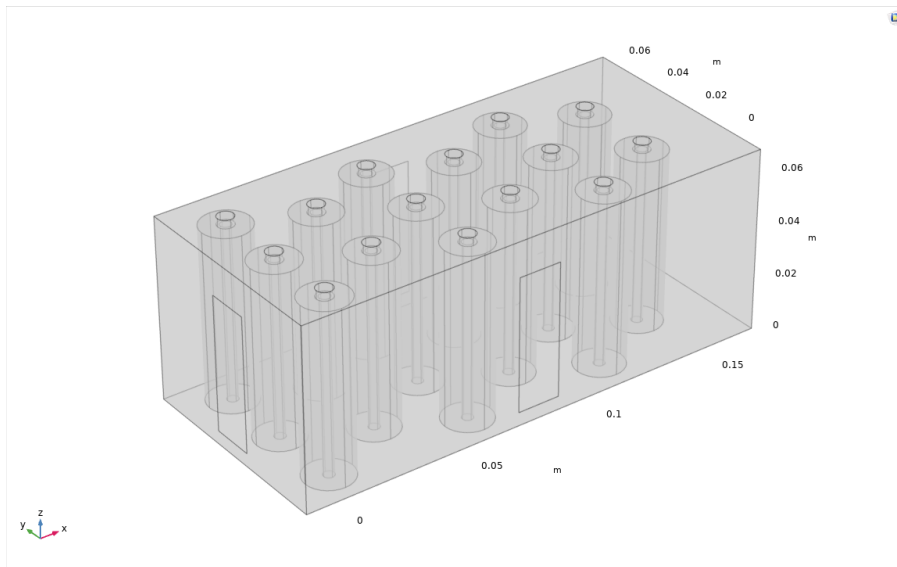


Fig. 4. COMSOL Multiphysics model used.

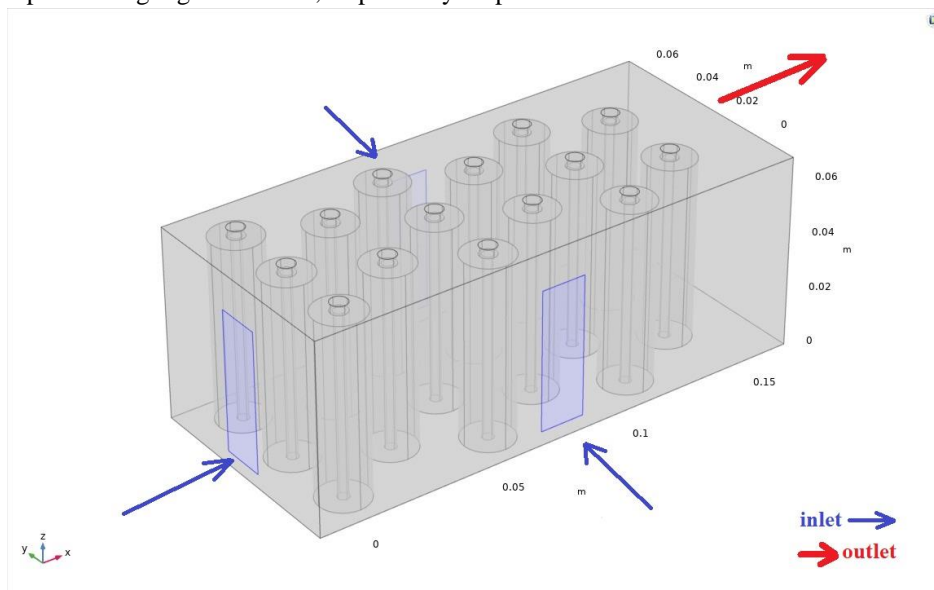
### III. SIMULATION RESULTS

The simulations carried out in this work followed the comparison of the recording temperatures in the Li-Ion type battery by varying a series of parameters. Thus, the cooling environment is a particularly important aspect. An unforced cooling of the laminar model was imposed (mass flow of  $1e-5$  kg/s). To highlight the influence of the cooling environment, three materials with different properties were used: R22, freon and ethylene. All are used as cooling media, and their main properties are highlighted in Table 1 [23, 24].

Table 1. Main properties of the used cooler agents [23, 24].

Property / Material	R22	Freon	Ethylene
Chemical formula	$\text{CHClF}_2$	$\text{CCl}_2\text{F}_2$	$\text{C}_2\text{H}_4$
Molar mass [g/mol]	86.47	120.91	28.054
Density [ $\text{kg/m}^3$ ]	3.66	1.486	1.178
Appearance [-]	colourless gas	colourless gas	colourless gas

Another important aspect that the present work brings into discussion is related to the placement of the inlet and outlet sockets of the cooling agent. Thus, as can be seen in Fig. 5 three distinct situations were simulated. Inputs are highlighted in blue, respectively outputs in red.



(a) Model 1

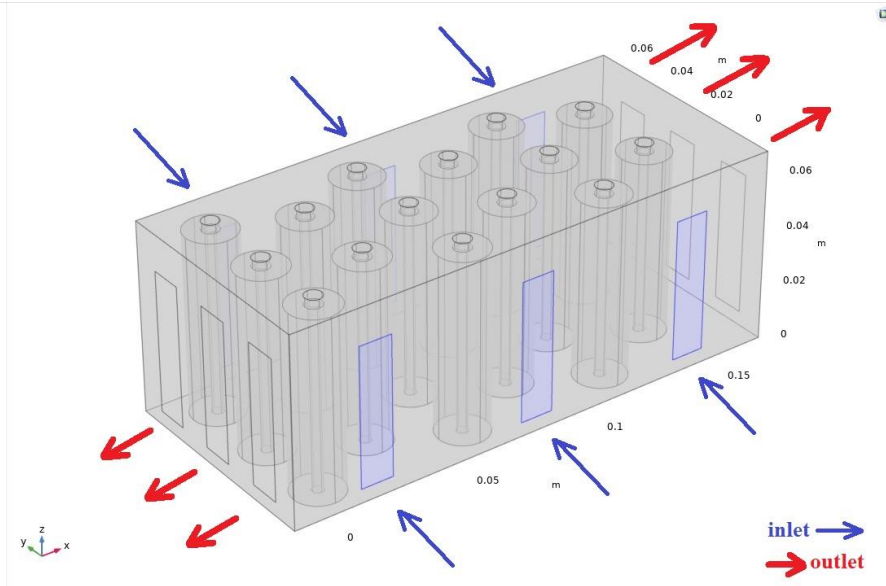
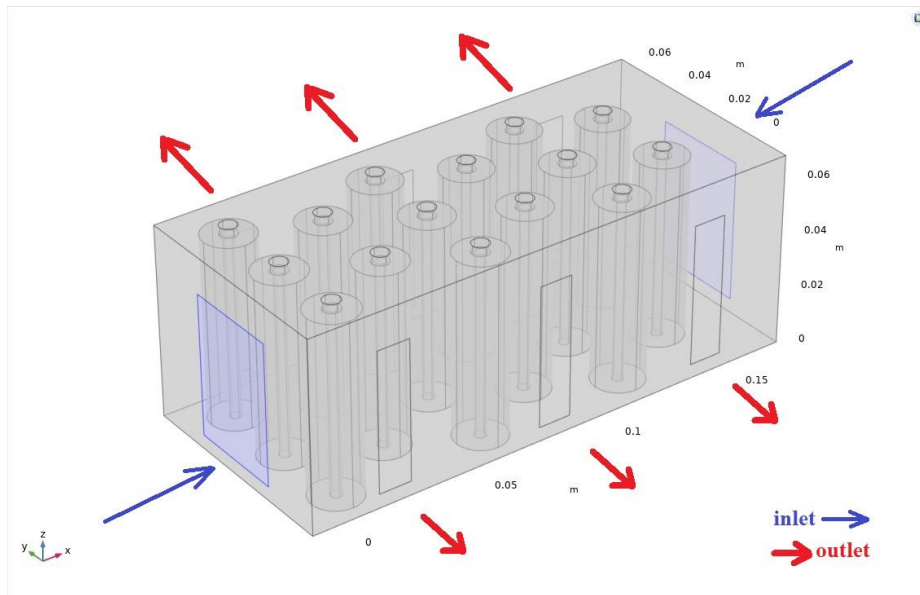


Fig. 5. Highlighting the input and output sockets for the simulated situations.

A. Model 1

The first model has a total of 3 entry surfaces and one exit surface (Fig. 5a). The total area of the entry surfaces is equal to 8308 mm<sup>2</sup> the exit surface is equal to 5508 mm<sup>2</sup>. Battery temperatures were analysed for the three coolants used. In Fig. 6 shows the simulation for ethylene cooling.

Using the data provided by Advisor, the run in COMSOL also offers the visualization of the battery charge rate (green line), respectively the cell potential (blue line) according to Fig. 7.

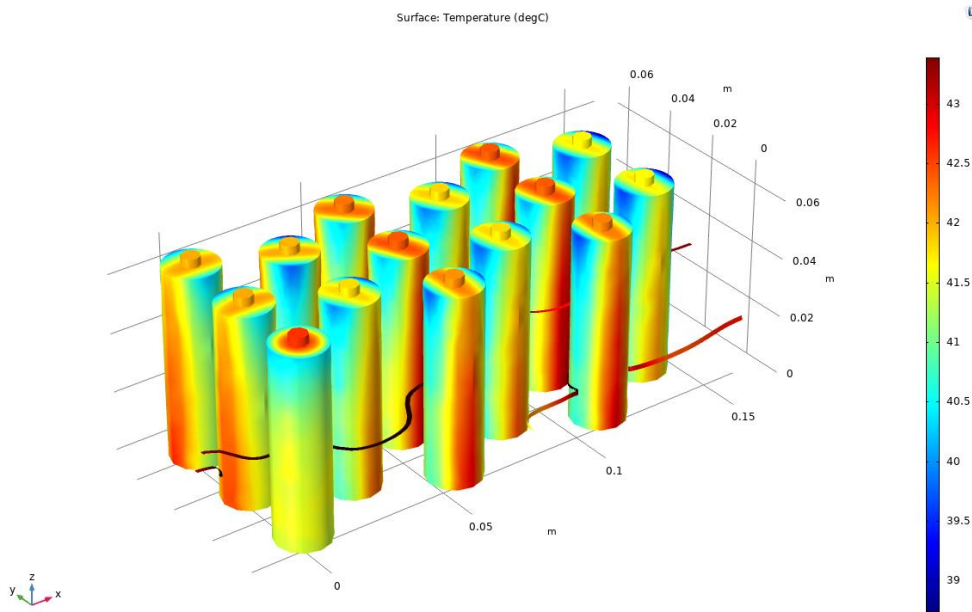


Fig. 6. Model of cells in the Model 1, showing the active cooling by the cooling agent (ethylene).

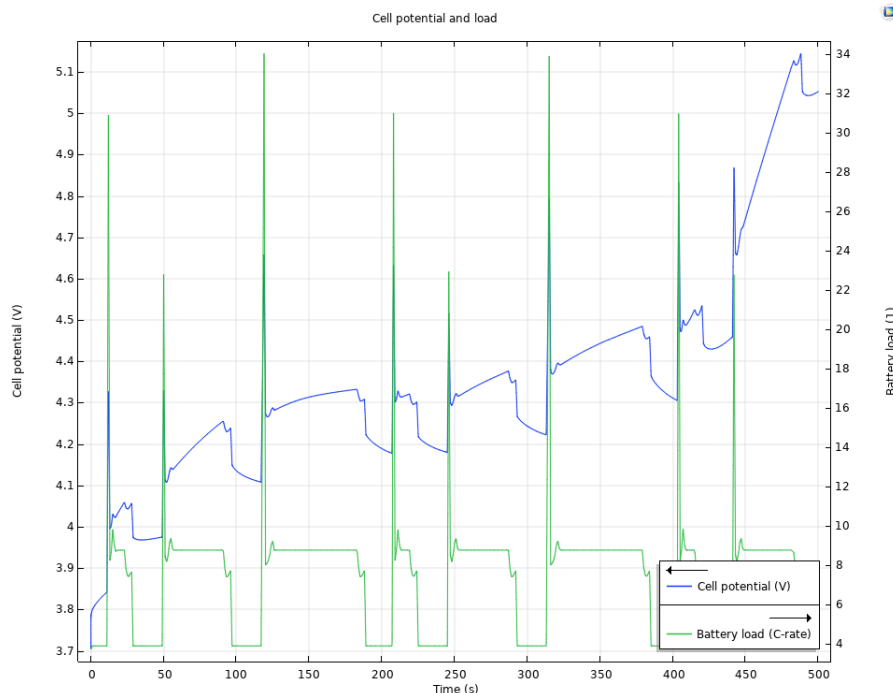


Fig. 7. Visualisation of cell potential (blue line) and battery load (green line) for the first 500 s of the NEDC.

To compare the influence of the cooling agent, in Fig. 8 shows a comparison between the temperatures difference recorded in the battery for the first 500 s of the NEDC cycle for the use of the three cooling agents. It is obvious that cooling with ethylene is a much better solution than with the other two modeled environments, the maximum temperature being less than half then freon. R-22 cooling agent is between them.

**B. Model 2**

The second model has a total of 2 entry surfaces and 6 exit surfaces (Fig. 5b). The total area of the entry surfaces is equal to 0.0035 m<sup>2</sup>, the entry surface is split into two equal parts of 0.00175 m<sup>2</sup>. The exit surface is equal to 0.0035 m<sup>2</sup>. In Model 2, the outlet surface is divided into 6 sections having an area of 0.000585 m<sup>2</sup> each. Battery temperatures were analysed for the three coolants used. In Fig. 9 depicts the simulation for freon cooling. Similarly, to Model 2, a comparison was made between the temperature differences recorded in the battery during the NEDC cycle portion. Fig. 10 illustrates this aspect, once again noting the significant reduction in temperature using ethylene.

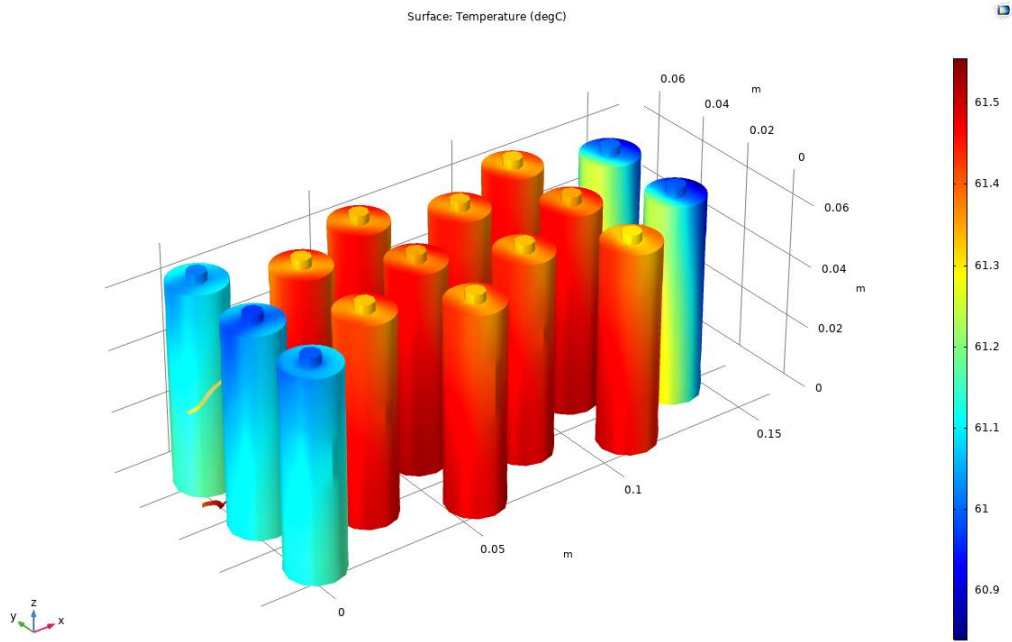


Fig. 9. Model of cells in the Model 2, showing the active cooling by the cooling agent (freon).

**Comparison between the temperature difference in the battery for Model 2**

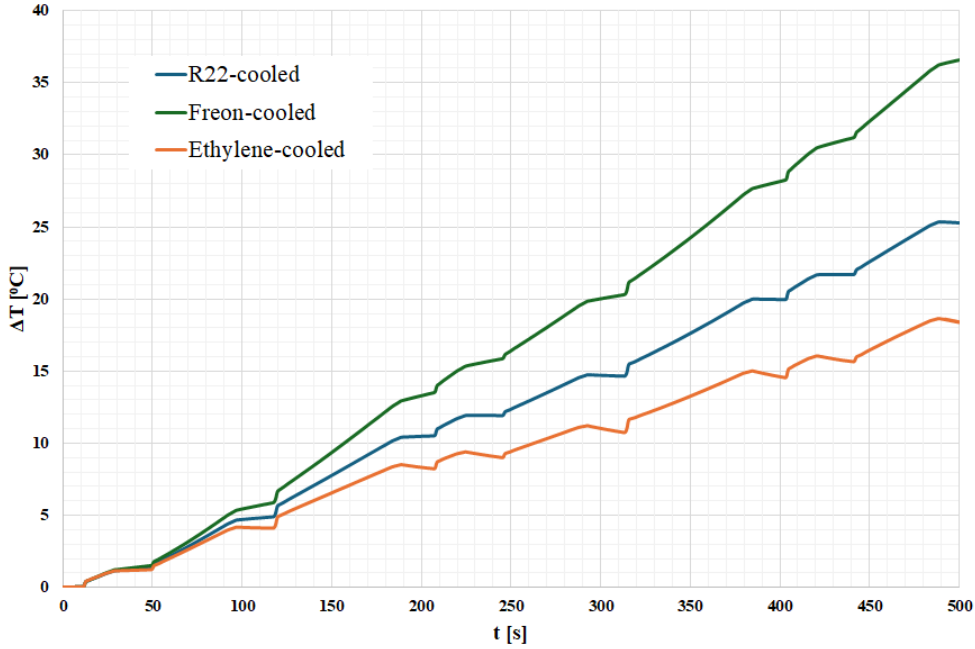


Fig. 10. Comparison between the temperature in the battery using Model 2 and the three cooling agents.

C. Model 3

The third model used a total input surface area of 0.05 [m] by 0.07 [m]. This input surface is divided into 6 equal inlet rectangular spaces along the walls of the battery container. The model is thought up to have an equal inlet surface of 0.0035 m<sup>2</sup>, respectively 0.0035 m<sup>2</sup> of output. In this case it is highlighted in Fig. 11 temperature distribution inside the battery for the use of ethylene cooling agent.

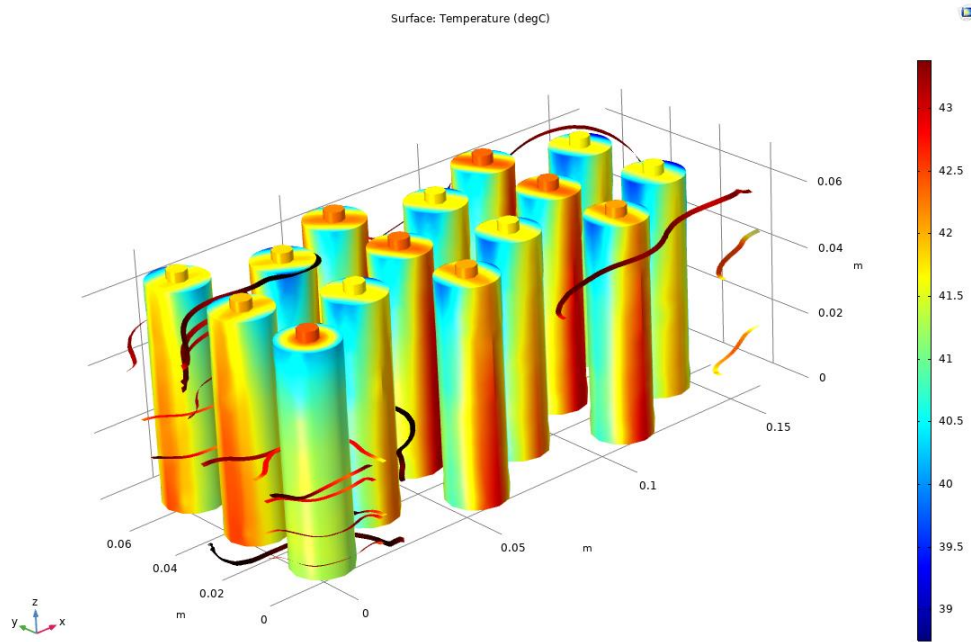


Fig. 11. Model of cells in the Model 3, showing the active cooling by the cooling agent (ethylene).

**Comparison between the temperature difference in the battery for Model 3**

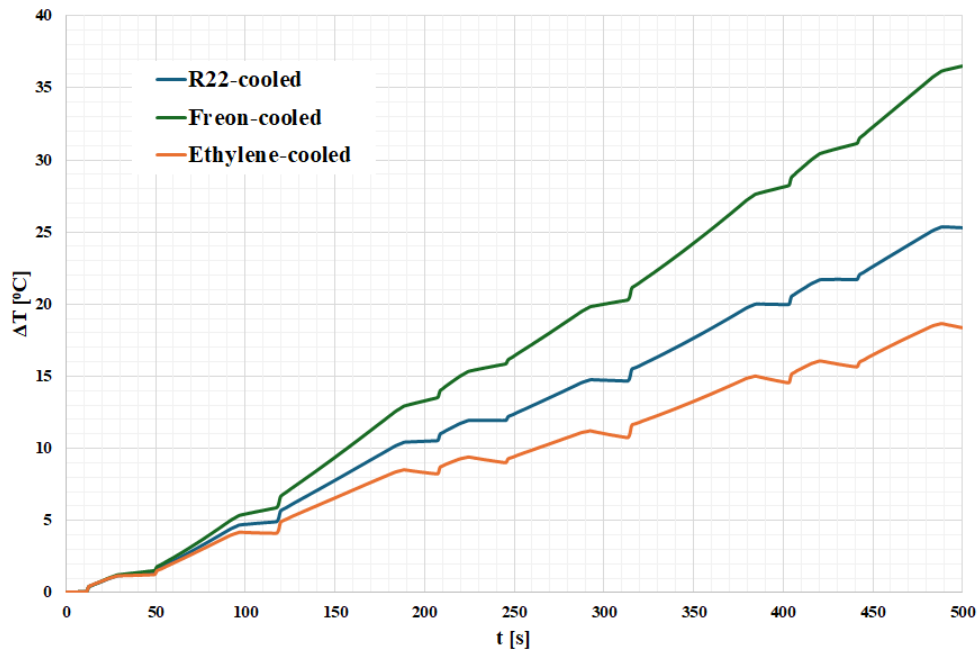


Fig. 12. Comparison between the temperature in the battery using Model 3 and the three cooling agents.

Therefore, it can be stated for all three analysed models that ethylene is the best cooling medium, followed by R22 and finally freon.

**IV. DISCUSSION**

The study presented in section 3 focused on a presentation of the three models and a comparison between the cooling agents used for each of them. The inlet and outlet surface areas are kept constant across all 3 models, this is done to maintain their comparability. However, it is also important to point out the advantages introduced by each of the presented models. Thus, in Fig. 13 shows a comparison between the three models for air cooling, and in Fig. 14 the same comparison surprises cooling with ethylene.

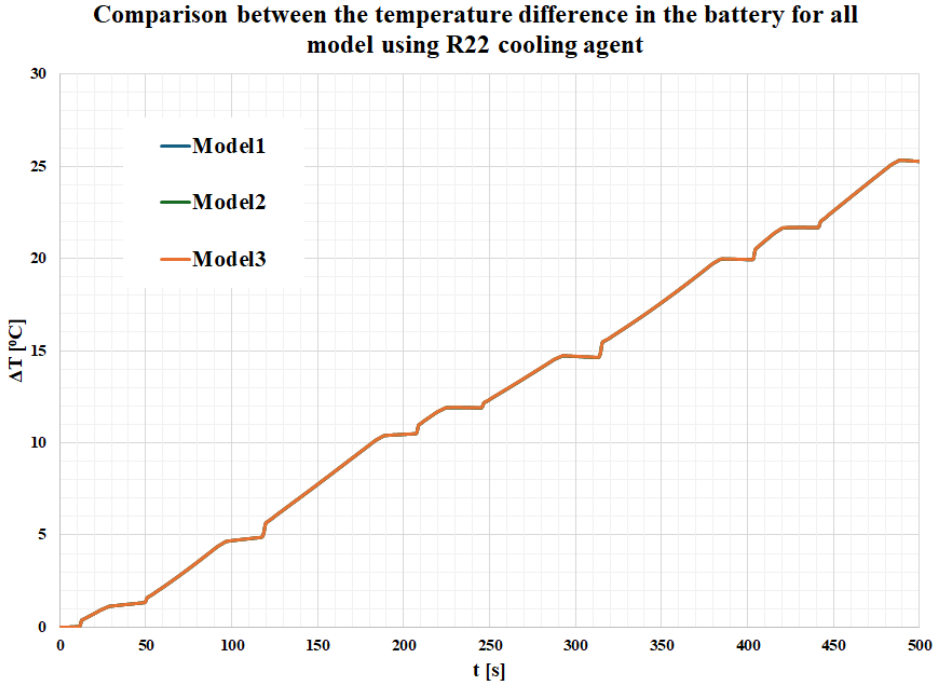


Fig. 13. Comparison between the temperature in the battery using R22 cooling for the three models.

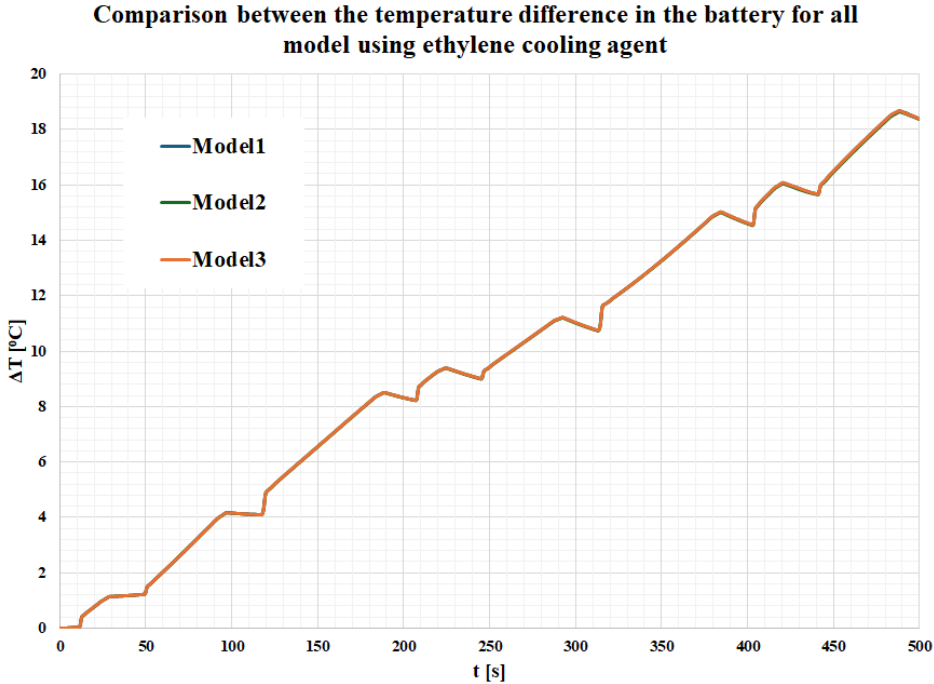


Fig. 14. Comparison between the temperature in the battery using ethylene cooling for the three models.

It can therefore be noted that regardless of the positioning of the input and output sockets, if the same surface of these is kept, for the same cooling medium.

### V. CONCLUSIONS

The study presented in this work followed the highlighting of some solutions to reduce the temperature in a Li-Ion battery with 15 cells. This desired is particularly important for any battery manufacturer in the automotive area. The proposed solutions are theoretical, but they can be the basis of further technological developments. To get closer to the real case, the first 500 seconds of the NEDC standard driving cycle were used and by with the help of Advisor, the real variation of the battery supply current was generated.

It started from 3 different models for positioning the input and output sockets and from 3 different cooling environments. The latter were selected from the COMSOL library and the use of colourless gases with similar properties was increased. For all three models, it was found that ethylene cools the enclosure best, followed by R22 and the last freon.

To emphasize the influence of the input and output sockets, it started from the idea of using the same surface both at the input ( $0.0035 \text{ m}^2$ ) and at the output ( $0.0035 \text{ m}^2$ ) with different positions and in different numbers. This study underlines the fact that their different placement or the number of sockets used does not influence the cooling mode for the same cooling agent used.

The solutions offered must also consider the economic aspects, because obviously cooling with ethylene is much more expensive than using different types of freon. In this sense, we consider that finding various constructive solutions that allow a more efficient cooling even with the use of the air-cooling agent must represent an essential objective in the subsequent developments of the manufacturers.

The work can be furthermore extended by carrying out other studies that may consider other driving cycles, their full use by using more powerful processors. Supplementary a study regarding the increase in thermal efficiency by intensifying the speed of the cooling agent, as well as by extending the surfaces of the input sockets and/or exit are also to examine.

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