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THE INFLUENCE OF TEMPERATURE AT CHARGING AND DISCHARGING THE LITHIUM-ION BATTERY

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Li-Ion batteries are used as an energy storage element for various applications, from portable electronic devices to electric cars. The present study aims to explore how temperature variations affect the charging and discharging process of Li-Ion batteries, both theoretically and experimentally. For the experimental part, we made a data acquisition platform where we tested the behavior of a Li-Ion battery at different temperatures, starting from ambient temperature (22ºC) and going in both directions, down to -20ºC and up to +40ºC. Both high and low temperatures can have more or less reversible adverse effects on battery capacity, charge rate, and overall performance. The subject is particularly important in optimising battery performance under different temperature conditions.

1. INTRODUCTION

In today's context, where battery technology plays a key role in technological advancement, Lithium, or Li-Ion batteries, are among the most widely used devices for energy storage and reuse and are present in a wide range of applications, from mobile electronic devices to electric vehicles, because this technology has several advantages, including a high energy density about its weight and withstanding a high number of charge-discharge cycles [1,2]. At the same time, they also have factors that influence their optimal functioning. Understanding the factors that affect battery performance is crucial to maintaining the highest possible battery performance and lifetime. These factors that bring stress to the battery occur in two ways. The first way is from the duty cycle, such as the type of load connected to the battery, and the second way is the environment, for instance, temperature, which is an important indicator affecting the capacity of lithium-ion batteries [2–3]. Temperature variation can be caused either by chemical processes occurring during the charging and discharging of the battery or by external factors such as ambient temperature or location (heating or cooling source). While small portable devices do not experience much thermal stress, electric cars must cope with extreme temperatures and differences of up to 20 ºC within a few hours, which can harm battery performance [2–4].

In this paper, we aimed to experimentally realize several charge-discharge cycles of a lithium-ion battery to show how the temperature level impacts its efficiency. The structure of the article is organized as follows. Section 2 presents some theoretical aspects of lithium-ion batteries. Section 3 describes the platform through which we simulated charging-discharging in MATLAB at different temperatures. The experimental platform, which includes the monitoring, data acquisition, and temperature control parts, is presented in section 4. In section 5, we included the comparisons between the results obtained in the simulations and the experiment with the theoretical part. Finally, section 6 is dedicated to the most important conclusions.

2. THEORETICAL CONCEPTS

As mentioned in the introduction, lithium-ion batteries are thermally sensitive, and prolonged exposure to high or low temperatures can cause premature performance and deterioration of battery life. Low-temperature exposure to batteries is caused solely by the environment and depends on geographical location, where there are either seasonally low or constant low temperatures throughout the year. In contrast, exposure to high temperatures is caused by the external environment or charge-discharge processes [5].

Exposure to a high temperature for an extended period can cause an electro-chemical degradation and, in the worst case, a so-called "thermal runaway" reaction. Thermal runaway is an overheating chain reaction and is specific to Li-Ion batteries; it can occur when the internal temperature exceeds certain critical thresholds. Other triggers for this reaction can be mechanical, overloading, or other internal battery problems. This reaction causes the temperature to rise exponentially, causing fires or explosions. It is a significant safety issue because the chemical structure of the wine accumulator becomes unstable at high temperatures, and the reactions become uncontrollable [6].

Several studies analyzed the behavior of lithium-based batteries according to the temperature to which they are exposed, concluding that thermal variations strongly influence their performance and durability.

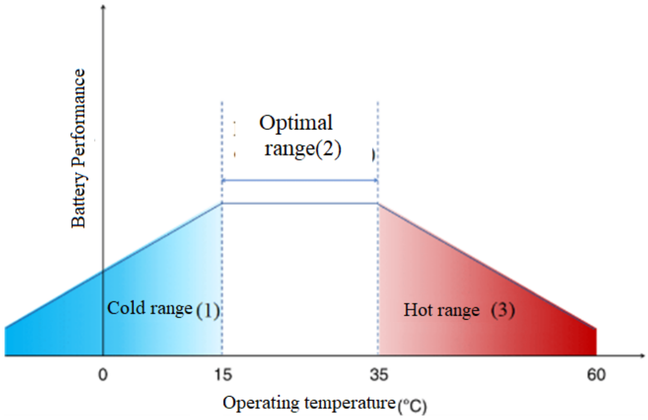

Fig. 1 – Optimum temperature range for Li-Ion battery use [2].

Much of the research has pointed out that there is an optimal temperature range for Li-Ion, and according to the graph in Figure 1, it can be seen that the optimal operating range (2) is in the range of 15-35 ºC; if the ambient temperature increases (3), the chemical reactions inside the Li-Ion cells also accelerate and the performance of the battery decreases, which can lead to a rise in the rate of battery electrochemical degradation. Excessive temperature can also damage the internal components of the battery and cause internal short-circuits, thus reducing energy storage capacity [7,8].

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The battery's electrochemical degradation results from several physicochemical processes taking place simultaneously. These processes lead to the growth and decomposition of the Solid Electrolyte Interface layer, electrolyte decomposition, impedance increase, material dissolution, structural degradation, particle isolation, current collector corrosion, loss of electrical contact, and electrode delamination. Increased impedance is the result of passive film formation on the surface of the active particles loss of electrolyte conductivity, and degradation of the electrical contact [7,8].

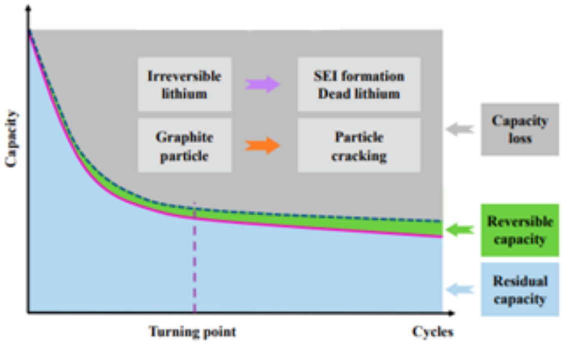

Fig. 2 – Schematic of battery degradation mechanisms during long-term low-temperature cycling (Lithium plating) [4].

Low temperatures can also reduce the performance of the Li-Ion battery. At very low temperatures, the electrolytes inside the battery can lose their fluidity, leading to increased internal resistance and reduced efficiency. Thus, the discharge capacity of the battery can be significantly reduced at low temperatures because Lithium plating occurs, which can also be seen in Fig. 2. Lithium plating is a phenomenon in which the lithium ions in Li-Ion batteries are deposited in the form of metallic lithium on the surface of the anode instead of being interspersed in its structure [7,8].

Considering the above, whether a single cell is used or whether several are connected in series/parallel to finally have a voltage-capacity characteristic necessary for the application where they are used, they cannot be used by themselves (like a lead-acid battery, for example), a system that monitors the operating parameters in the circuit and outside it must be connected to them. This system is called a battery management system (BMS). The BMS is therefore used to extend as much as possible the lifetime of lithium batteries to increase their performance, balance the capacity of cells, and prevent overcharging and undercharging. This works by monitoring multiple parameters like voltage, current, and temperature of the battery or the entire battery pack via temperature sensors, and, if necessary, it can activate the protection systems installed on the battery [9–11].

3. SIMULATION PLATFORM

For the simulation part of this research, we considered a 3.7 V 4.4 Ah Li-Ion battery, for which we tested both the discharging and the charging process at several temperature levels.

For the discharge, we implemented the circuit in MATLAB/Simulink according to Fig. 3 to test the batteries at all five temperature levels.

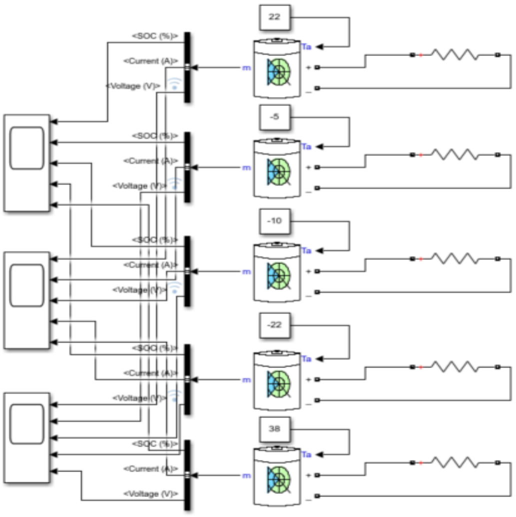

Fig. 3 – Battery discharge circuit at multiple temperature levels.

This contains the 5 Li-Ion batteries, which have temperature as input parameters. A 4 Ω resistive load was connected to them. We used a demultiplexer to which we connected an oscilloscope to visualize the parameters provided by the accumulator during the process.

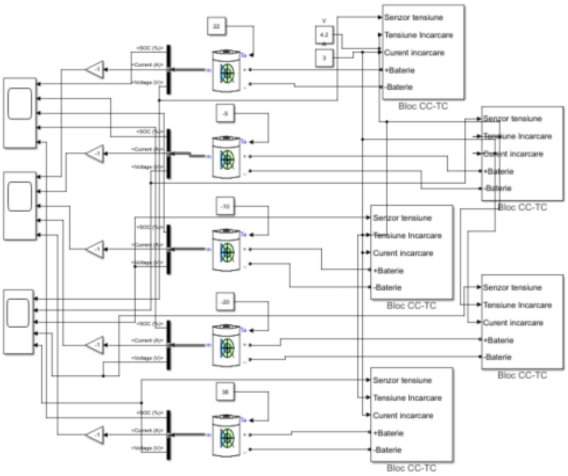

Fig. 4 – Battery charge circuit at multiple temperature levels.

We also implemented the charging tests in MATLAB/Simulink, the circuit shown in Figs. 4 and 5 to test the batteries at all five temperature levels. Fig. 4 contains the 5 Li-Ion batteries, which have temperature as an input parameter. Each battery is connected for the charging process to a Constant Current—constant Voltage (CC-CV) block [12,13].

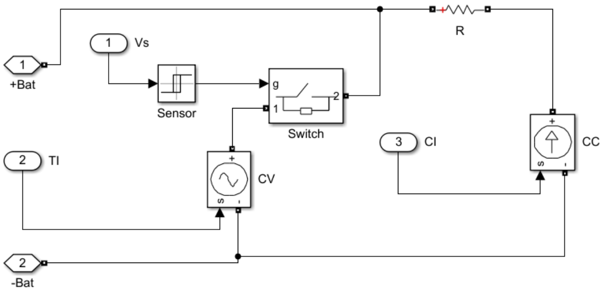

Fig. 5 – Battery charge circuit CC-CV controller.

This block (Fig. 5) includes sensors for measuring voltage and current during charging. The block also monitors the state of charge (SOC) and charging voltage to ensure that the parameters remain within optimal limits. To visualize the parameters provided by the battery during the process, we used a demultiplexer to which we connected an oscilloscope.

4. EXPERIMENTAL PLATFORM

To be able to do these tests in the experimental version on an actual battery, besides the circuits realized in MATLAB/Simulink, we designed a dedicated system that takes care of both maintaining the temperature at a set level and of data acquisition during the charging and discharging process of the battery. It memorizes several parameters, which we consider relevant in analyzing the thermal impact on Li-Ion battery performance. These parameters are:

- Battery terminal voltage;
- Current through the circuit;
- Battery surface temperature;
- Time to start process;
- Counter for measuring the total of recorded values.

Starting from the fact that we know which parameters we want to monitor, we realized the circuit in Fig. 6, based on which we are going to make the measurements.

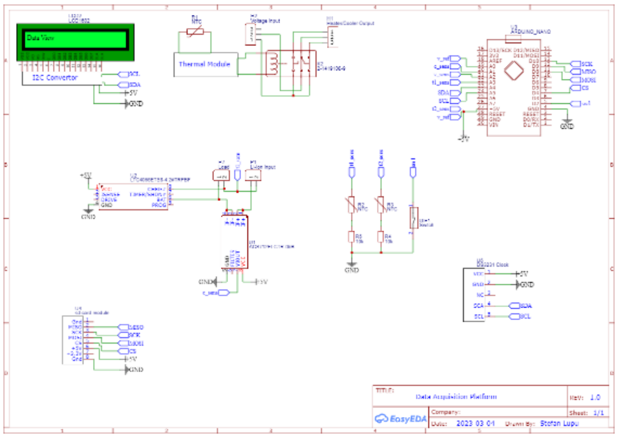

Fig. 6 – Data acquisition system circuit.

Using the wiring diagram, we realized the actual platform, as shown in Fig. 7, as an overview. It contains several elements that work individually. With the system, we want to be able to see these parameters during the charging and discharging of a Li-Ion battery at different temperatures.

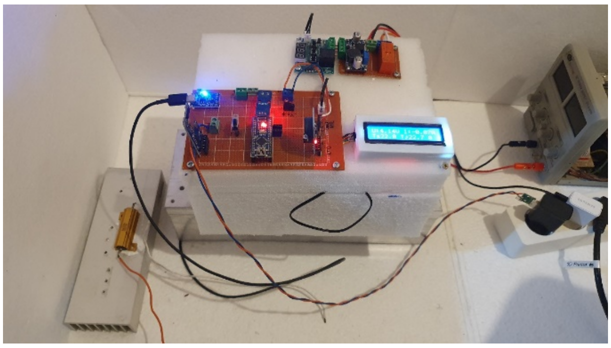

Fig. 7 – Data procurement system – overview.

We have used insulating sponges to create a thermally insulated area to control the temperature and place the battery pack.

For the low-temperature part of the test, we used two Peltier modules (Fig. 8, frame 1) placed between two heat sinks: one for high-temperature dissipation and the other for low-temperature dissipation.

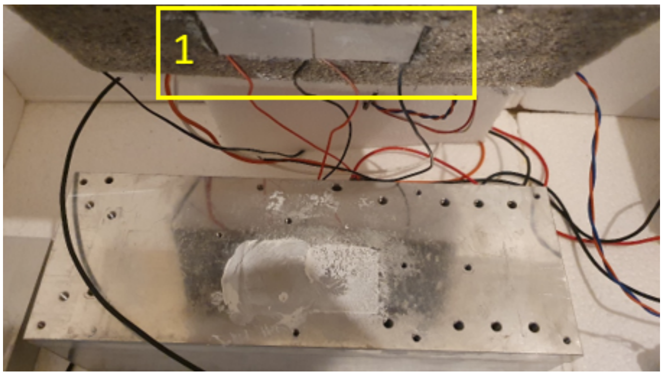

Fig. 8 – Cooling elements –Peltier module.

The Li-Ion battery (Fig; 9, frame 1) used in this experiment is 4980 mAh, with a nominal voltage of 3.7 V DC. We discharged it using a 4 Ω, 50 W resistive load (Figure 10, frame 4) and charged it with a switched-mode source, with 230 V AC input voltage and 5 V DC output voltage and TP4056 charging module mounted on test printed circuit board (Fig; 10, frame 1).

We heated the enclosure with a 4 Ω, 50 W power resistor (Fig. 9, frame 2) on the heat sink for the high-temperature test.

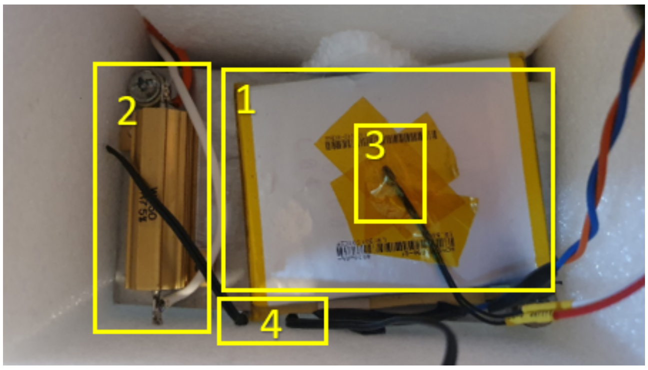

Fig. 9 – Data acquisition system – internal components.

The temperature controller in Fig. 10, frame 3, operates the components responsible for heating and cooling. On the test printed circuit board (Fig. 10, frame 1), we collected the elements with which the measurements are made, such as the current sensor, the charge-discharge module, the microSD card module necessary for saving measurements, and the clock module for high accuracy when measuring the time interval during the tests.

The board also contains the inputs for the temperature sensors (Fig. 9, frames 3 and 4), the terminals for powering the system, the terminals where the battery will be connected, and those where the load will be connected.

We chose to display the measured parameters on display (Fig. 10, frame 2) to observe the environment's temperature in real-time and start the data acquisition and charge/discharge test only when the battery is at the desired temperature. The display is also used to monitor other measured parameters, so we know when to stop the process.

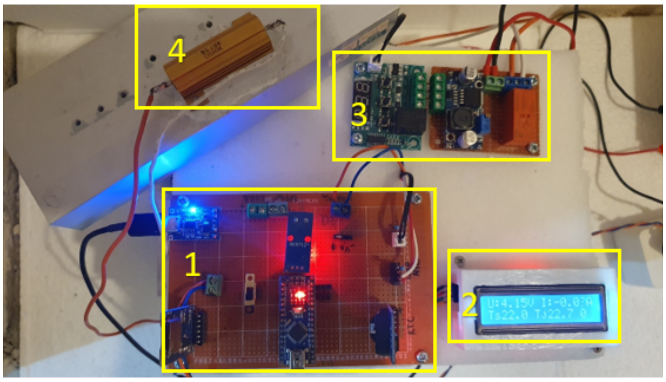

Fig. 10 – Data acquisition system – external components.

5. SIMULATIONS AND EXPERIMENTAL RESULTS

We performed both simulations and experimental tests for five temperature ranges. We made a first measurement at the ambient temperature, which fell within the optimal operating range, to use as a reference for the other measurements. We continued with three sets of measurements for temperatures in the low-temperature range. Finally, we also made a set of temperature measurements for the high-temperature range, which was near the upper limit of the range (Fig. 1).

The actual temperatures used to take the data acquisition for the chosen battery type mentioned above are the following:

1. Acquisition at normal temperature, noted Tn, range [22; 25] ºC at discharge, respectively at charge;
2. Low temperature acquisition, denoted Ts_v1, range [-5; -8] ºC at discharge and charge respectively;
3. Low temperature acquisition, denoted Ts_v2, range [-10; -14] ºC at discharge and load, respectively;
4. Low temperature acquisition, denoted Ts_v3, range [-20; -21] ºC at discharge and load, respectively;
5. High-temperature acquisition, denoted Tr_v1, range [37; 38] ºC at discharge and load, respectively.

Following the simulations for discharging at the five simultaneous temperatures, we obtained the voltage behaviour at the battery terminals concerning time, shown in the graph in Fig. 11.

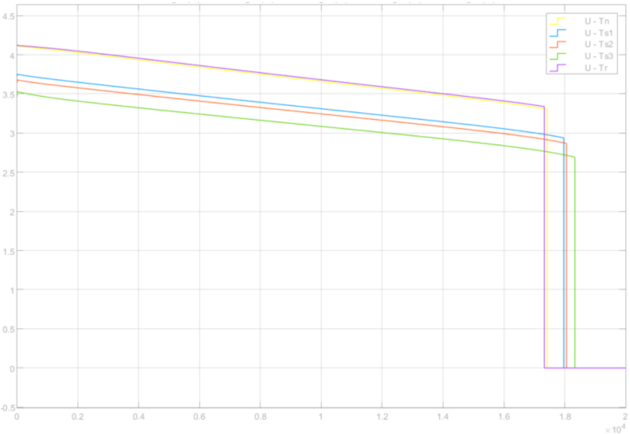

Fig. 11 – U-values as a function of discharge time – results from simulation.

Table 1.
Maximum, minimum, and average experimental values were obtained by discharging the Li-Ion battery.

	Discharging LiIon Tnormal	Discharging e LiIon Tlow_v1	Discharging LiIon Tlow_v2	Discharging LiIon Tlow_v3	Discharging LiIon Thigh_v1
Total values	21425	18275	15192	12179	21847
U_max [V]	3.8227	3.207	3.1338	2.6771	4.1242
U_min [V]	2.4996	2.4957	2.4949	2.4977	2.4947
I_max [A]	-0.8518	-0.7409	-0.7156	-0.651	-0.745
I_min [A]	-0.5908	-0.5644	-0.55	-0.2793	-0.5263
time_total [hh:mm:ss]	03:45:26	03:13:05	02:40:30	01:54:20	03:25:09
Temp_med [ºC]	25.19	-4.25	-10.27	-20.72	38.22

For the experimental data acquisition, each set of measurements was saved in ".txt" files, which were subsequently post-processed using Excel and plotted using MATLAB. After each measurement, the accumulator had rest times to reach the required temperature.

After the first processing, we obtained the data concentrated in Tables 1 and 2, where we highlighted the values for voltage, current, and temperature (maximum, minimum, and average) obtained by the Li-Ion battery's discharging (Table 1) and charging (Table 2) processes. Also, for each measurement, the battery started from being fully charged or fully discharged—this was done under normal environmental conditions.

After the first processing, we proceeded to the next step, where we plotted (Fig. 12 and 14) using the MATLAB tool. All five sets of values were measured during battery discharge and charge.

By displaying both tabular and graphical values, we could easily see the consequences of the thermal misuse of a Li-Ion battery.

In the case of the discharges shown in Table 1 and the graph in Fig 12, the first aspect identified is the difference in the total time elapsed from the start to the complete discharge of the battery, *i.e.*, the temperature value is inversely proportional to this time. If at a normal temperature, we obtained a total time of 03 h 45 min 26 sec, in the cases where we exposed the battery to an increasingly lower temperature, we noticed a decrease in this time of 14 %, 29 %, respectively, 49 %. We had the same result for exposure to a higher temperature, where we measured a time difference of 9 %.

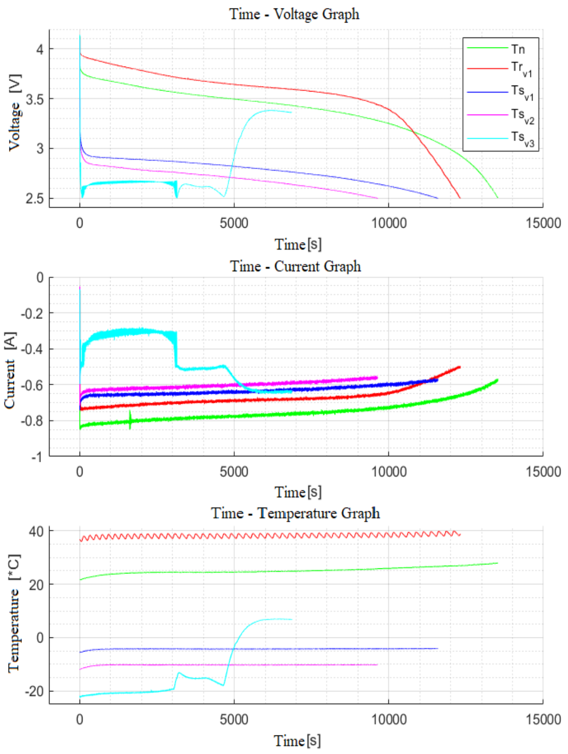

Fig. 12 – U-I-Temp values as a function of discharge time – results from the data acquisition system.

The thermal factor also affects the current through the circuit; we observed that it is limited the lower the temperature. In the data acquisition performed for low temperatures, we identified a drop of up to 23 % in current, considering the maximum values recorded.

The same limiting effect is visible when the temperature is higher than expected; experimentally, we measured a current 12 % lower than that measured at the normal temperature.

Regarding the voltage measured at the battery terminals, we again identified the same decreasing effect when the load was connected.

We also obtained a similar behavior regarding the voltage at the terminals, as expected, in the simulation, as can be seen in Fig. 12. For cases where the battery was exposed to low temperature, the difference was up to 30 % compared to the voltage measured under normal conditions.

On the other hand, the voltage behaved differently when the battery was kept at a temperature above the recommended one; in this case, we observed that it did not have a sudden drop, but, on the contrary, it remained at a value of ~8 % higher than the reference one. We deduce that this happened because the thermal agitation accelerated the chemical processes inside the battery. Following the simulations, but in this case for charging mode at the five simultaneous temperatures, we obtained the behavior of the voltage at the battery terminals about time, shown in the graph in Fig. 13.

Table 2

Maximum, minimum, and average experimental values that were obtained by charging the Li-Ion battery.

	Charging LiIon Tnormal	Charging LiIon Tlow_v1	Charging LiIon Tlow_v2	Charghing LiIon Tlow_v3	Charghing LiIon Thigh_v1
Total values	36182	18856	11726	21587	25148
U_max [V]	4.1869	4.167	4.178	4.2083	4.2077
U_min [V]	3.8051	3.7865	3.7459	3.8119	3.4042
I_max [A]	0.744	0.2837	0.2575	0.4387	0.9102
I_min [A]	0.0168	0.0727	0.0294	0.0165	0.0181
time_total [hh:mm:ss]	06:19:55	03:17:44	02:02:52	02:56:35	03:55:41
Temp_med [ºC]	22.41	-7.65	-13.44	-20.26	37.99

In the case of the charges performed represented by Table 2, respectively, and the graph in Fig. 14, the first parameter that we observe affected is, as in the case of the results obtained at discharge, that of the total time elapsed from the beginning to the full charge of the battery between the tests performed. Once again, the inverse proportional relationship is maintained, which makes the charging time appear to be up to 68 % shorter when exposed to low temperatures and up to 38 % shorter when exposed to high temperatures. This is not positive because when the battery temperature returned to the optimal range, it also returned to its ability to store energy.

In the end, these have a very large margin of error. Even if the battery seems charged, it is not, and we can identify this by the Ts_{v3} measurements in Graph 14. After the battery apparently seemed charged, we turned off the cooling source, and progressively, with it, the charging current increased.

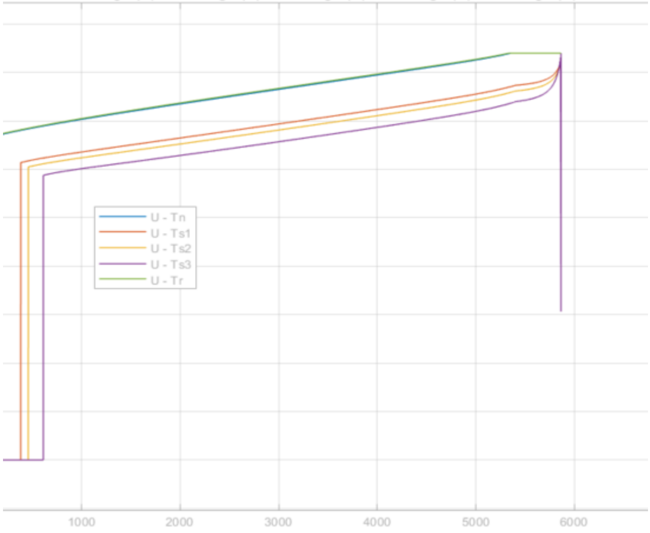

Fig. 13 – U-values as a function of charge time – results from simulation.

The same effect was obtained when discharging at low temperatures for the Ts_{v3} measurement in Graph 14. After the battery was wholly discharged, we switched off the cooling source. When the temperature rose, the discharge current began to go in the same direction as an absolute value. From this, we can conclude that the measured values were strongly influenced negatively by the thermal factor.

In this case, we notice that the voltage at the terminals in the case of the simulation (Fig. 13) results compared to the one measured in the experiment (Fig. 14) shows a different behavior due to the protections that are implemented in the case of the MATLAB/Simulink model.

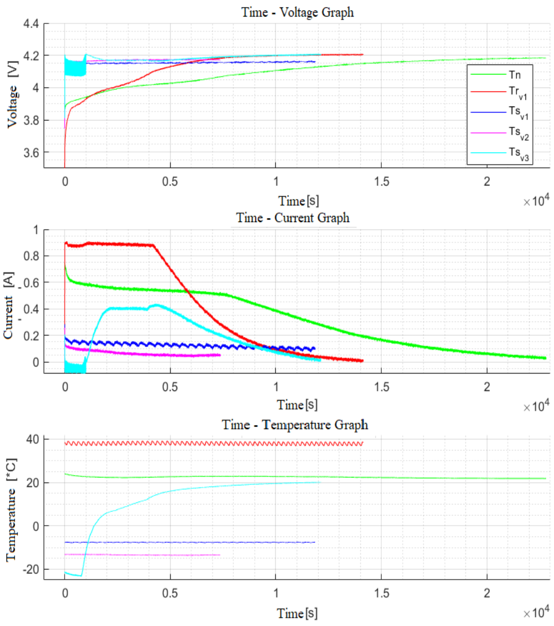

Fig. 14 – U-I-Temp values as a function of charge time – results from the data acquisition system.

However, at the end of the charging process, it is observed that although the charging method is CC-CV and in that interval, it should already be on the CV loop, there is a sudden increase in voltage. At the same time, when the accumulator with the lowest temperature reaches the nominal voltage and practically stops charging, there is a sudden voltage drop, which we also observe in the case of the experimental model.

6. **CONCLUSIONS**

The data analysis in the simulations and experiment showed that the thermal factor significantly impacts the battery's performance, lifetime, and even user safety. At low temperatures, it loses its capacity, which is undesirable, especially in the case of electric cars where, to charge the accumulator, a charging station must be available. At high temperatures, in addition to the loss of parameters, there is also the risk that the chemical reaction cannot be stopped, and the battery may catch fire, which could endanger the user. It is, therefore, important that this is carefully monitored and must be kept constant or at least within the optimum operating range. At present, existing BMS systems are successful in this. Still, in the future, new technologies assisted by artificial intelligence will take these monitoring and control systems to another level, or possibly, as battery technology improves, they will no longer be sensitive to temperature variations.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ştefan Lupu: literature review, simulations, experimental platform, data acquisition, experimental data processing, article writing.
Dan Floricău: involved in planning and supervising the work; contributed to the final version of the manuscript.

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