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Experimental investigation of lithium-ion battery cells for model-based thermal management systems

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Abstract: Thermal management is one of the most investigated features of modern energy storage systems, especially in automotive applications. The design of a battery pack in an electric vehicle requires accurate knowledge of the electric and thermal behavior of every single component. This work presents experimental measurements and numerical analysis for the simulation of the electro-thermal status of a battery cooled utilizing either natural convection or direct liquid cooling. The effect of different discharging currents, and ambient temperature has been experimentally investigated in natural convection, then a multi-domain model has been validated with the measurements and used to simulate the battery-electric and thermal status with liquid cooling. The most critical condition is characterized by low temperature and high current. Results carried out evaluating the overall input/output energy balance have highlighted that the battery performance at low temperatures is improved using low current rates.

Keywords: Battery, Experimental measurements, Thermal management, Electro-thermal model, Energy

1. INTRODUCTION

Nowadays, main concerns about climate change and the increasing need in reducing air pollution, related to the road transport sector, have supported the rapid development of the hybrid and electric vehicles (PEVs) market. Most PEVs are supplied by lithium-ion batteries because of their high performance in terms of energy/power density and life span. In addition, the wide adoption of these storage technologies has caused relevant falls in their costs with an average reduction of about 90 % from 2010 to 2021 (BloombergNEF's (2021)).

On the other hand, lithium batteries in PEVs applications are generally pushed to their limit to draw maximum performance in terms of vehicle electric driving range and high-power charging/discharging capability (Kohlmeyer et al. (2019)). In this case, prevention of thermal runaway (TR) is considered a crucial point, since it can be a cause of battery pack spontaneous combustion and explosion, seriously affecting the safety of vehicles and passengers. In particular, the main causes of TR can be identified in over-heating issues and non-uniform temperature distribution in the battery pack during charging/discharging operations (Robinson et al. (2014)).

Based on the above considerations, it is clear that the development of proper Battery Thermal Management Systems (BTMSs) plays a key role in guarantying safety, durability, and performance for the overall vehicle (Bandhauer et al. (2011)). These systems should pursue simultaneous objectives of avoiding non-uniform temperature distribution among battery cells and ensuring proper operative temperature range for the overall battery pack. (Zichen et al. (2021)). In particular, the optimal design of BTMS remains a challenge, although much research has been conducted on this topic. Nowadays, air and liquid-based BTMS are used in most applications. Air cooling systems are still preferred for small vehicles, because of their advantages in terms of costs and simplicity. In this case, series, parallel, or mixed cooling configurations can be used. Both direct and indirect (e.g. tube cooling, cold plate) liquid cooling systems have shown different advantages since they can be more efficient in controlling the battery temperature reducing at the same time the on-board noise level and the overall size of the battery pack (Xia et al. (2017)). Phase change materials are also proposed as an interesting solution regarding their use in hybrid mode with liquid cooling (Amalesh et al. (2022)).

Most approaches for choosing and sizing BTMSs are based on theoretical evaluations carried out in a simulation environment. These evaluations can be conveniently performed at the single-cell level and then extended to the whole battery pack. In this regard, various models are proposed in the scientific literature with a specific focus on the storage cells, whose thermal characteristics generally depend on complex electrochemical reactions and electro-thermal conversion. In particular, storage cells' behavior can be analyzed based on various simulation approaches, which mainly consist of electrochemical (EM), machine learning (ML), and circuit-oriented models (ECM) (Tamilselvi et al. (2021)). EMs are considered high-fidelity models, for the simulation of chemical processes related to electrodes and electrolytes of the cells. In most cases, information about those processes is obtained through the application of the Electrochemical Impedance Spectroscopy (EIS) technique. Examples of this modeling approach can be found in (He et al. (2022)). The main drawbacks of EMs are related to their high computational requirements, which generally do not justify their application either for real-time control algorithms or for long-time simulations. ML techniques are generally characterized by low computational complexity, and acceptable model fitting performance, which generally depends on the choice of proper training data sets. Examples of this approach can be found in (Li et al. (2021)). ECM techniques present the main advantage of reflecting input-output relationships of storage cells based on equivalent electric circuits, with direct correlations between thermal and electric parameters and low computational effort (Orcioni et al. (2017)). Although this methodology represents a well-known approach, it requires proper experimental activities for complete thermal and electric characterization of the storage cell under test.

Starting from the above context, the main contribution of this paper is referred to a complete electro-thermal characterization of a lithium battery cell. In this regard, an ECM simulation model has been parameterized and validated, through specific experimental tests. The obtained results allow the implementation of an experimental knowledge base on lithium cell behaviors in different thermal-electric operative conditions. The proposed simulation model also allows investigations on the use and effectiveness of liquid cooling systems in terms of optimal cell temperature and energy demand. The evaluations reported in this paper can be further applied as a reference in designing the structures of battery packs or planning cooling strategies.

2. EXPERIMENTAL SET-UP

It is well-known that the actual performances and behavior of lithium-based energy storage systems are strongly affected by their electric and thermal operative conditions (Zichen et al. (2021)). In this regard, the laboratory set-up allows obtaining a complete experimental analysis from both the above points of view. All the experimental tests reported in this paper are referred to the case study of a 4890 Ah - lithium-ion battery cell. The current collectors are made of aluminum (positive) and copper (negative). The cell features a LiC_6 anode and a $LiMn_2O_4$ cathode. The maximum, nominal, and cut-off voltage are 4.2V, 3.8V, and 2.8V, respectively. The dimensions are 100x110x3mm with a weight of 75 g. The laboratory bench for electric tests is based on a controlled DC power supply, working in combination with an electronic DC load. These devices are respectively set in master-slave communication mode to perform ultra-fast zero-crossing switching between charging and discharging operations. The realized configuration allows for carrying out electric characterization tests with current and voltage values up to 120 A – 80 V. Both above devices can be set to work in a restricted voltage range to obtain detailed evaluations also at single-cell voltage level. The laboratory bench is equipped with a USB communication system, which allows setting and control of the charging/discharging cycle through a proper user-friendly software interface, installed and configured on a remote PC.

During the tests, cell temperature control is performed through a climate chamber, which can be set to either fixed or variable temperatures in the range of -40 ÷ +180°C. A functional scheme of the experimental setup is reported in Figure 1. The acquisition system of the laboratory test bench is based on a National Instruments cDaq 9188 equipped with voltage and current acquisition modules. In this regard, a software interface has been realized in the Labview environment to monitor cell behavior during the test and to store all the experimental data for the required analysis. During the tests, cell electric terminals have been directly connected to voltage acquisition modules, whereas current measurements have been performed through the use of LEM LA25 current sensors. A single PT-100 probe has been used for cell temperature monitoring. The proposed electric test bench allows the realization of steady-state and dynamic charging/discharging cycles for the storage unit under test. Those cycles can be set by the operator through a specific software interface. Further details on the test bench are reported in (Balsamo et al. (2020)).

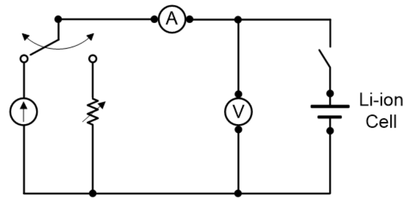


Fig. 1. Functional scheme of the experimental set-up

3. MODELLING

3.1 Battery Electric Model

As well-known in the scientific literature (Huria et al. (2012)), ECM parameters are strongly dependent on battery Temperature, *T*, and State of Charge, *SoC*. Therefore, a proper procedure for the identification of parameters must consider the behavior of the storage cell in different electric and thermal conditions. In this regard, Multi-Step Test cycles (MST) are proposed in (Huria et al. (2012)) as a possible experimental procedure able to identify ECM parameters with good levels of approximation.

For the research activities described in this manuscript, the proposed ECM with one RC branch has been implemented in Matlab-Simulink ® environment. MST has been carried out through the experimental laboratory set-up, for different cell temperature values. Starting from the obtained experimental results, in terms of cell voltage, current, and temperature, an iterative procedure has been performed in Matlab® environment to find optimal parameter values, minimizing least square errors among measured and simulated data. The parameters values and their variation with the *SoC* have been previously published in (Sequino et al. (2021)).

3.2 Battery Cooling System Model

The battery thermal and electrical performance is simulated using a model of an Electric Vehicle (EV) battery cooling system developed in Simulink® and available online by (Gazzarri (2022)). To validate the model with data collected in the climatic chamber where no cooling system is applied, the heat exchange to the surrounding environment is simulated by natural convection (Figure 2). Subsequently, a direct liquid cooling system with a radiator is implemented. The simulated system is composed of a radiator that exchanges heat with the ambient air and a cold plate with cooling channels that direct the liquid flow below the battery. For the air-cooling in the radiator, a constant airflow speed of 10 m/s is set to simulate a typical average velocity of a vehicle. While, according to the results of a previous paper, a blend of propylene glycol (10%) and water (90%) is used in the liquid cooling channels (Sequino et al. (2021)). All the schemes and complete information on the cooling system are reported in (Gazzarri (2022)). The control policy for thermal management is based on a thermostatic on-off control with a hysteresis cycle. It activates for a +1°C difference between the set and the actual temperature and deactivates when the difference is +0.1°C. In Figure 2, the battery simulation sub-system in natural convection, with the input current and the output temperature, is shown. In the 'battery' block, the battery is indicated as Pack 1, which is a pack with 1 element. The blue lines represent electric connections. Current from outside the block enters the positive pad after passing in an amperemeter and a voltmeter then comes out from the negative pad. The block 'f(x)=0' represents the model solver characteristics. The 'T' in the bottom-right corner of the battery saves the temperature value to the record. The orange line starting from the 'H' in the upper-left corner of the battery is relative to heat flux, calculated with Eq. 1, which goes to the sub-system named 'convection'. Here, the heat transfer between the battery and the ambient is simulated. It is composed of a convective heat transfer block connected to the constant ambient temperature source.

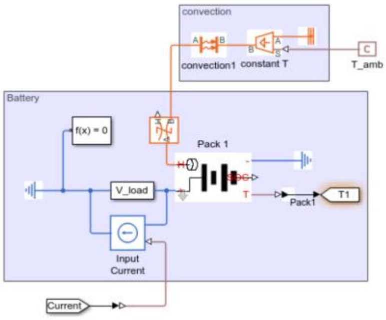


Fig. 2. Multi-domain model of the battery with natural convection heat transfer in Simulink®

3.3 Theoretical evaluation of the internal heat generation

During its charging/discharging operations, the battery heats up because of the Joule effect generated by the current flow and the chemical reactions between the electrodes. The power generated per surface unit, q_{gen}, depends on battery current and voltage values according to the following equation (Scrosati et al. (2015)):

$$\dot{q}_{gen} = I\left[-\frac{dV_{oc}}{dT}T + (V_{oc} - V)\right] \cdot \frac{1}{A} \tag{1}$$

where I is the current, V_{oc} is the open-circuit voltage, and V is the actual voltage measured at the battery terminals. The first derivative term is related to the reversible entropy change in the cell; whereas the second term is the heat related to cell polarization. Since the derivative term is very small (lower than 0,001 V/°C (Farmann et al. (2017))), the main driver of the power loss is the difference between the open circuit and the actual voltage. The actual voltage can be directly measured during battery charging/discharging operations, whereas the V_{oc} can be reliably measured only after a long rest time. Therefore, this last value must be evaluated in advance to obtain a proper estimation of q_{gen}. For the case under investigation, the temperature gradient from the core to the surface of the battery can be neglected because of the small thickness of the battery. The Biot number that compares the effects of convection and conduction is very lower than 1 (Bi<<1) (Landolt et al. (1999)).

4. RESULTS AND DISCUSSION

The experimental results reported in this section mainly referred to the characterization of battery cell performance, model parameters identification/validation, and evaluation of thermal effects using a typical air or liquid cooling system. All the tests have been carried out through the described experimental set-up with the battery cell fully charged.

4.1 Analysis of voltage signals and evaluation of actual battery cell capacity

Experimental tests aimed at the characterization of battery performance in terms of voltage drops and actual capacity for different values of temperature and discharging current. Figure 3 reports voltage behavior for three discharging tests at different current values with the temperature of the climate chamber set at 25°C and 0°C. The initial voltage value for all the analyzed cases is 4.2V, which corresponds to a 100% *SoC*. Higher discharging currents involve higher initial voltage drops, after that the voltage continues to decrease up to the cut-off value. Low C-rates guarantee longer discharging times while, with a 2C discharging rate, the cut-off voltage is reached after just a few minutes. With regards to the effect of ambient temperature, the experimental results at 0°C show a significant reduction in battery performance that worsens with higher currents. In comparison to previous tests, the initial voltage drop decreases according to the R0 reduction. With a discharging rate of 1C, the test duration decreases by 30%, whereas for discharging rate equal to 2C the initial voltage causes the reaching of the cut-off voltage value.

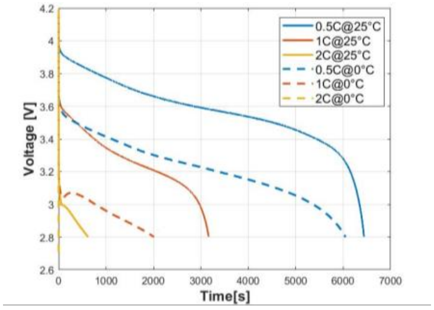


Fig. 3. Voltage signal versus time at three discharge currents for 25 ° C and 0°C.

To have a better overview of the dependency of battery performance on testing temperature and discharging current, actual capacity values have been evaluated through the Coulomb counting method in the discharging phase. The evaluated actual capacity presents a linear trend versus time since the discharging current is characterized by a constant value, therefore the final value is reported in Table 1 for the tests at 25°C and 0°C. For the cases at 0.5C and 1C at 25°C, the evaluated actual capacity is respectively 4.48 Ah and 4.31Ah which are close to the nominal value of 4.89 Ah evaluated by the manufacturer. Different considerations can be made at 2C, where the actual capacity of the battery cell is very low, reaching the value of 1.19 Ah, which is about 24% of its nominal value. As already shown for the analysis of voltage signals, also these results highlight non-linearities of battery behavior with increasing current ratings. At 0°C, a general reduction of capacity for all the discharging rates analyzed can be appreciated. In particular, the evaluated capacity for the 0.5C test decreases from 91.6% to 84.2% in comparison to the battery cell nominal capacity. Moreover, the effect of the temperature is stronger at a higher current. Similar behavior can be observed for the case at 1C, where the actual capacity reaches about 55% of its nominal value. The capacity for the test at 2C is not reported because it has been interrupted after a few seconds when battery cell voltage suddenly reaches the cut-off value; the extracted capacity is about 0.12% of the nominal one, which is too low to be considered as the available capacity in this condition.

Table 1. Battery capacity and discharging efficiency versus temperature and rate.

	25°C		0°C	
C-rate	Actual Capacity [Ah]	Efficiency [%]	Actual Capacity [Ah]	Efficiency [%]
0.5	4.478	91.6	4.118	84.2
1	4.307	88.1	2.735	55.9
2	1.189	24.3	N/A	N/A

4.2 Analysis of battery cell temperature

Net temperature, that is the difference between the battery temperature and the constant ambient temperature, during discharging and resting phases, has been measured and reported in Figure 4 for different discharging rates with the thermal chamber set at 25°C and 0°C. For all the tests, a temperature increase has been evaluated for a period that corresponds to the complete discharging phase. At 1C and 0.5C, the battery cooling during the resting phase is recorded. The temperature of the battery returns to the initial ambient temperature meanwhile, only the first instants of the cooling phase are available for the case at 2C.

The temperature of the battery is the result of a balance between the heat generated and the heat dissipated. In the beginning, the heat generated is accumulated in the battery producing an increment of temperature, indicated by the sharp initial slope of the curves in the graph. The heat exchange to the surrounding environment via natural convection is limited because of the small temperature difference. When the battery reaches a certain temperature, different for each condition, the heat transfer increases, and the rate of temperature variation decreases. This phase is visible in the graphs where a local peak appears. The temperature seems to oscillate and increase again with a lower slope. In particular, at 2C this behavior is not visible because of the low duration of the test. From the analysis of results, it is clear that higher discharging rates have involved higher temperature gradients. This behavior is in line with Eq. 1 where the internal heat generation, which drives the increment of temperature, depends on current values, internal resistance, and voltage. Also, from the thermal point of view, battery behavior seems to present a non-linear trend with the discharging current. In particular, the gap is 0.5°C at 0.5C, 3.5°C at 1C, and 10.5°C at 2C considering the first local peaks of temperature for the three investigated cases. The same discharging tests have been also performed in the climate chamber at 0°C. A higher gap for the local peak has been evaluated, about 1°C and 6°C at 0.5C and 1C, respectively. At 2C, the short time of the test has not allowed a reliable evaluation of the temperature gradient since it remains equal to the ambient conditions, due to the thermal inertia of the battery cell. Higher temperature gradients at a room temperature of 0°C can be explained using Eq. 1 considering the dependence on internal resistance R0, which is higher at low temperatures. Also, for this case, a local peak and a following low slope phase can be detected. While a faster cooling phase is obtained, because of the higher temperature gap reached in this case.

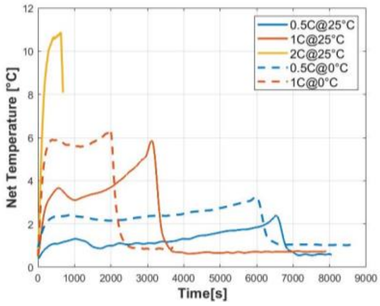


Fig. 4. Temperature versus time at three discharge currents at 25 ° C and 0°C.

4.3 Electro-thermal model of the battery cell

Experimental results in terms of measured current, voltage, and temperature have been used in the models to evaluate electric and thermal parameters for the battery cell electro-thermal model. In this section, experimental results are used for model calibration and validation in natural convection conditions with the surrounding environment. Once, the model is validated, the model with direct liquid cooling is used to evaluate the performance of the battery cell at a controlled temperature.

Figure 5 reports the comparison between experimental and simulation results for voltage and temperature at 25°C and 0°C with a discharging rate equal to 1C, considered as the reference condition. The modeled voltage well matches the experiments. At 25°C, an underestimation of about 0.1 V is observed at the end of the discharging phase at 3000, however, its effect on the temperature is not significant. The initial increment of temperature is well predicted by the model. Then it misses the oscillation matching again the measurements at 2000s. The estimation of the thermal parameters with the ECM allows to reproduce with high fidelity of the battery thermal status and this can be appreciated in the last part of the discharge phase where a sudden temperature increment is measured and well modeled. Finally, the cooling down phase is also predicted with good approximation both during the temperature decrement and the stabilization. Similar considerations can be made at 0°C, where a small overestimation of the voltage and a 1°C temperature overestimation are seen at the end of the discharge phase still producing a good prediction of the electro-thermal status of the battery. Analyzing the percentage error, for the voltage signals, the maximum is 3.4% at 2800s and 1C. For the temperature, it is 3.6% at 1000s at 1C and arrives to 16% at 2000s at 0.5C because of the low absolute value of the temperature.

After the validation of the model with the experimental data in natural convection, the liquid cooling system is simulated. The model used is the one described in the *"Battery Cooling System Model"* section. The comparison of the battery temperature with discharging current 1C at 25°C and 0°C is reported in Figures 6 A) and B). At 25°C, the temperature increases by 3°C to about 500s for natural convection and remains at a constant value as long as the current is applied. After the end of the discharging phase, the cell temperature returns to the ambient value. Conversely, with liquid cooling, the system activates immediately preventing the temperature to increase during the whole discharge process.

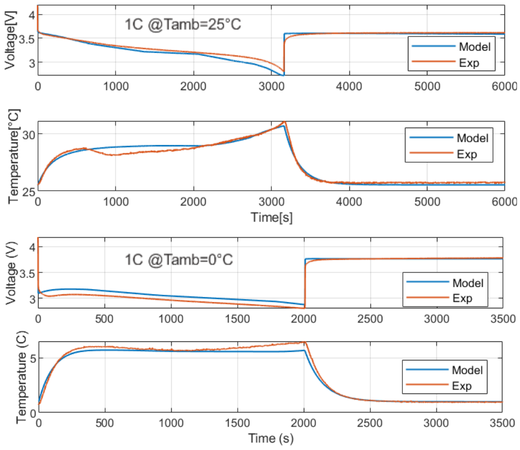
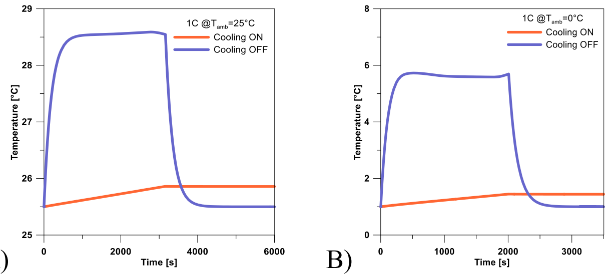


Fig. 5. Simulated and measured values voltage and temperature for 1C discharge at 25°C and 0°C.



A) B)

Fig. 6. Simulation results of battery temperature with liquid cooling On and Off for a 1C discharge at 25°C (A) and 0°C (B).

At about 3000s, the difference between the actual and the set temperature is lower than 1°C, hence the cooling system does not activate, resulting in a final temperature of about 26°C. Similar considerations can be made for the case at 0°C in figure 6 B where an increase of temperature of 5°C can be appreciated at 0°C whereas it is 3°C at 25°C. This can be ascribed to the higher internal resistance at low temperatures that affects the heat generation according to Eq. 1. With the cooling systems, the increment of battery temperature is prevented even if the working temperature is lower than the set value. This happens because the cooling liquid, which has a certain mass, can absorb the heat produced by the battery even without additional refrigeration. It is interesting to observe that the final temperature of the battery is higher with liquid cooling than with natural convection because of the increased temperature of the liquid after absorbing the battery heat. Results related to the other investigated conditions with different currents are in line with the presented results and then are not reported.

4.4 Input and output energy of the system

Simulation results related to temperature behavior with and without the direct liquid cooling system can be used to evaluate the amount of energy extracted from the battery for its thermal management. From the practical point of view, on one side, higher operating temperatures involve lower internal resistance but require more energy for cooling. Conversely, at low ambient temperatures, the cooling system is almost not used, allowing to save energy while the battery performance is worsened.

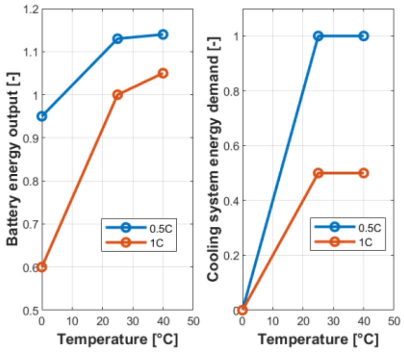


Fig. 7. Battery energy output and cooling systems energy demand at different temperatures. Data are normalized by the conditions 1C, 25°C.

To better highlight the energy requirements of the cooling system, the overall battery available energy and the energy demand of the cooling systems are compared during a discharging test at a constant current. An additional operating point with an ambient temperature of 40°C is selected to expand the range of the data. The results are shown in Figure 7 for different discharging rates and temperature conditions. In this case, data are normalized to the results of the discharging test at 25°C and 1C. The available energy indicated as energy battery output (graph on the left), is negatively affected by the reduction of ambient temperature. A lower discharging rate ensures higher efficiency providing a higher energy output, and reducing the disadvantages of low temperatures. Concerning the cooling systems energy demand, it is zero at 0°C because the cooling system is not activated under the threshold of 25°C. The value for the case at 25°C of ambient temperature and 1C is 1 as it is used as a reference. While at 0.5C is 0.5 because half of the heat is generated by the battery. At 40°C similar results than at 25°C are obtained for both the C-rating used. When the ambient temperature is higher than 25°C, the temperature set is increased as well because the radiator cannot ensure a temperature lower than the ambient.

5. CONCLUSIONS

This work investigates the electric and thermal behavior of a single battery cell, to be assembled in a battery pack. An experimental investigation analyzes in detail the battery performance at different ambient temperatures and discharging currents. Whereas simulation models are built to simulate the operation with different cooling systems and to make an energy balance in different conditions.

Experimental results clearly show the negative impacts of higher current rates and low-temperature operative conditions in terms of actual capacity. The maximum temperature gap has been observed for 2C at 25°C, with the battery temperature increasing in a non-linear way with the discharge current.

The battery cell model with natural convection to the surrounding environment has been validated with the experimental results and provided a good match with the voltage and temperature data. The model of the battery cooled through a direct liquid cooling system has been used to simulate the operation with temperature control. For the cases under investigation, rapid and effective control is performed. At low temperatures, 0°C, the battery performance is worsened but the energy demand of the cooling system is zero. Hence, when working at low ambient temperature it is advisable to reduce the discharging current rate to increase the energy output of the battery pack.

The experimental knowledge coming from the activities reported in this paper represents support for the prediction of the on-board battery pack behavior, to make storage cells work in optimal conditions from both the electric and thermal points of view.

Further investigations can be considered to take into account the impact of aging on battery ECM parameters. Future investigation will also address the experimental analysis and modeling for different cooling system configurations both for single cells and for the whole battery pack.

6. ACKNOWLEDGEMENTS

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