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Air Cooling of Li-ion Batteries: an Experimental Analysis

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Electric vehicle industry has been rapidly developing internationally due to the renewed interest in low- or zero-emission vehicles. So far, Lithium-Ion batteries, is the technology that best fits the needs of electric vehicles, due to their large specific energy density and specific power, making these cells ideally suited for high rate-of-discharge applications such as during acceleration. In spite of this, there are safety concerns using Lithium-ion cells because of the use of high energy materials. Heat is a major battery killer and Lithium secondary cells need careful temperature control. Operating at high temperatures brings on a set of different problems which may result in the destruction of the cell: unless heat is removed faster than it is generated, a thermal runaway may occur. Tests with an air cooling system were carried out using an experimental loop specially designed: the tests were performed on a module consisting of four pouch cells, manufactured by EiG, connected in series. The module was discharged with a current of 80 A (4C discharge) and cooled with air at velocity ranging from 0 to 7 m/s. It was found that it is possible to completely discharge the batteries using air velocities higher than (or equal to) 4 m/s. Increasing the air velocity the temperature difference between the centre of the cell and the electrodes decreases. In spite of this, it was not possible to reach a uniform temperature distribution within a cell, and within the pack, using air as cooling fluid.

1. Introduction

In a battery pack, the cells are assembled in groups or modules to obtain the required capacity, and modules are connected in series to provide the required voltage. For high-power battery packs, such as those for HEV and PHEV applications, a considerable amount of heat can be generated in the cells as a result of high discharge currents during duty cycles, causing the rapid rise in cell temperature. For optimal performance of a battery pack, working temperatures of the cells in the pack should be maintained within a proper range (ideally between 20 and 40 °C), and the temperature distribution in the cells should be as uniform as possible. Thus, a well designed thermal management system is required to ensure good battery performance, safety, and high capacity. Different cooling methods have been proposed and implemented: air cooling (Sabbah et al.,2008; Yang et al., 2015; Lou Y., 2007; Sun H.et al., 2012; Jung DY et al., 2002; Zolot M.et al., 2002), liquid cooling (Valøen et al.,2005) heat pipe cooling (Guo et al., 2011) and Phase Change Materials (PCM) cooling (Sabbah et al., 2008; Kizilel et al., 2008; Duan et al., 2010). Although liquid cooling and PCM cooling ensure better cooling effect, air cooling is highly favoured for its overall performances (light weight, low cost, long life, etc.).
In the literature, a lot of numerical studies analyze the battery thermal behavior using air cooling systems. However, few papers present experimental investigations of the system performances under various operating conditions (different air velocities and temperatures). In the present work the cells of a battery pack, provided with air cooling, were carefully and locally monitored with thermocouples during intense discharge cycles. The tests were performed on a module which consists of four pouch cells connected in series; the temperature uniformity within a cell and from cell to cell were analyzed under various operating conditions.

2. Experimental apparatus

An experimental loop was designed to test air as cooling fluid to remove the heat from a battery pack. The test station was set up to run the tests using cooling air at different flow rates and inlet temperatures: this is useful for the assessment of the operative thermal limits in different working conditions.

The loop employed in the experimental campaign (shown in Figure 1) is equipped with: four axial fans disposed in pairs; an electric pre-heater, to provide the desired inlet air temperature; an anemometer, to measure the air mass flow rate; a channel, long enough to assure a velocity profile completely developed, in order to guarantee a proper operation of the anemometer; the test section with the battery module (four cells connected in series); an air mixer and two thermocouples, to measure the outlet average air temperature; the cycler Eltra E-8325 (voltage 0 ÷ 18V, current 80 Amax in charge 150 Amax in discharge); the acquisition system developed with Labview.

The square channel is constructed with insulated panels made from rigid polyurethane foam, coated with aluminium foils. The total length is about of 5 m (with a calming length of 2,40 m) and the internal dimensions are 106x106 mm.

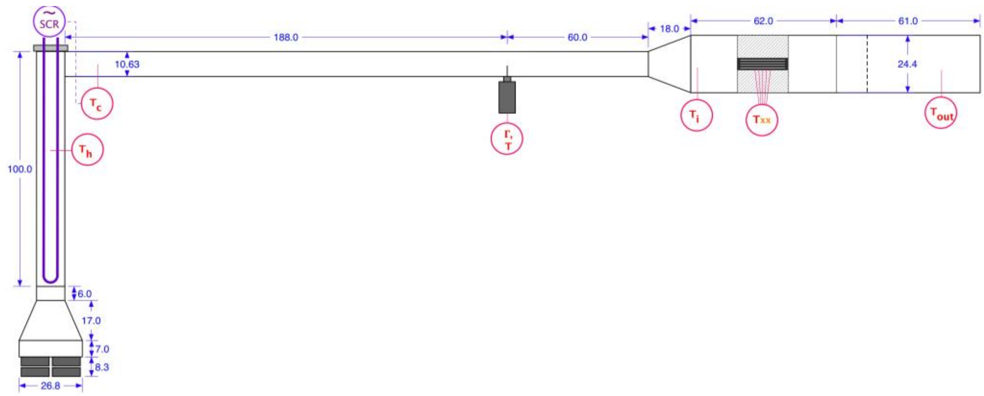


Figure 1: Diagram of the experimental loop and test section (T_h=temperature of the heater, T_c=temperature of the channel, Γ=air mass flow, T_{xx}=temperatures monitored in the battery pack, T_i=inlet air temperature, T_{out}=outlet air temperature).

The battery module (Figure 2) is located in a channel of 306 x 244 mm and the air passes through the batteries longitudinally. The module consists of four pouch cells connected in series. NMC ($LiNi_yMn_yCo_{1-2y}O_2$) based batteries produced by Energy innovative Group (EiG) have been used for the tests; the nominal specifications, provided by the manufacturer, are shown in Table 1.

Table 1: Specification for the EiG battery.

Nominal Capacity	20 Ah	Maximum discharge current	200 A (peak of 10s)
Standard Discharge	0.5 C	Operating Temperature	-30°C ÷ 50°C
Standard Charge	0.5 C	Recommended Charge Temp.	0 ÷ 40°C
Maximum continuous discharge current	100 A	Storage Temperature	-30 ÷ 50°C
Maximum continuous charge current	20 A	Dimensions	216x129x7.2 mm

The cells are spaced 3 mm apart: the distance between the batteries is maintained by a rigid support made of a non-conductive material.

The the cells were part of a battery pack already used to supply energy to move a cable car in a different investigation (Conte et al., 2010). A previous experimental campaign (D'Annibale et al., 2014) showed that there is a significant difference in the thermal behaviour of new and old cells. Aging of the batteries seems to play a significant role since, at the same discharge/charge conditions, both the temperature increases and the local intensification of heat losses are higher for the old cells. The old NMC pouch batteries were selected to make the cooling tests to analyze the worst thermal conditions.

Based on the results of the previous thermographic campaign (D'Annibale et al., 2014), 14 thermocouples were positioned on both sides of the batteries (Figure 2b). Commonly. aging mechanism mainly occur near the two electrodes and hot spots have been found either in the correspondence of the cathode current collector or of the anode: accordingly 10 thermocouples are located on the battery surface close to the current collectors.

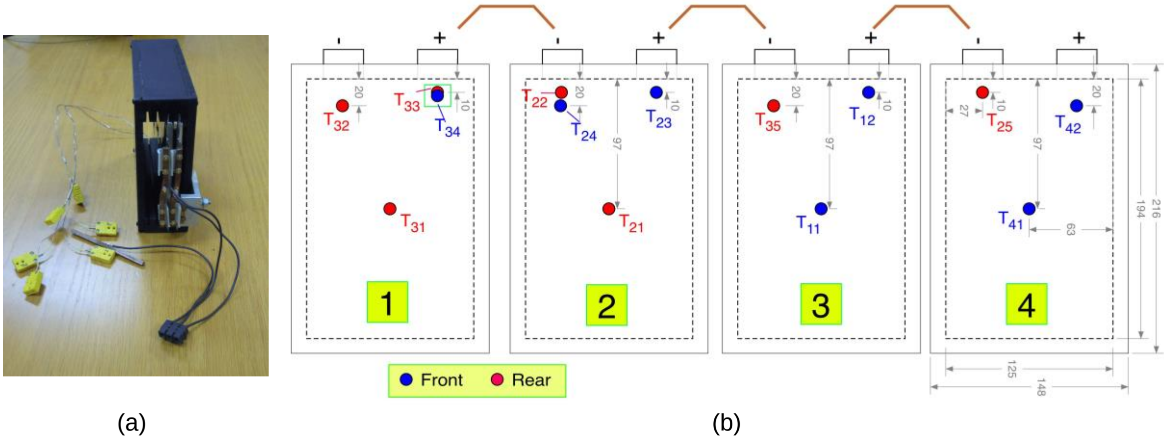


Figure 2: (a) EiG battery module during construction. (b) Thermocouples disposition on the cells of the module.

3. Experimental procedure and results

The portable cycler (Eltra E-8325) was used to charge and discharge the battery pack.The higher temperatures are reached discharging the batteries (D'Annibale et al., 2014): for this reason the cooling tests were made with a high discharge current, in order to evaluate the efficiency of a battery cooling system in the worst thermal conditions. A 4C discharge rate was used for the tests because the previous results (D'Annibale et al., 2014) showed that also the new cell exceeds the temperature limits with a current value of 80 A.

The experimental tests were carried out with an air velocity ranging from 0 to 7 m/s in the gaps between the batteries.

For each experimental test the values of the air velocity, the Reynolds number and the initial temperature, are given in the table below (Table 2) and the flow regime for each test is specified.

Table 2 Matrix of the experimental tests with air.

Air Velocity (m/s)	Re	T_0 (°C)	Regime flow
0	0	20	Natural Convection
0	0	30	
0	0	40	
1.2	473	19	Laminar Flow
2.4	949	18.6	
4	1580	18.6	
4	1478	30	
4	1396	40	
7	2757	19.2	Transitional Flow

The tests have been interrupted when the temperature of 48 °C (two degrees below the maximum temperature limit) was reached on the battery surface to avoid the degradation of the Li-ion cells and to work in safe conditions. the tests at air velocity equal to 0, 1.2, 2.4 m/s had to be stopped before the end of the discharge.

It is possible to completely discharge the batteries (down to the minimum voltage value imposed of 11.7 V) using an air velocity v≥4 m/s. At the highest tested velocity (7 m/s), the maximum temperature reached by the battery pack at the end of the discharge is much lower (38°C)than the limit value (50°C) provided by the manufacturer (see Table 1); the minimum discharge voltage value is reached in a shorter time compared to the case of an air velocity of 4 m/s (Figure 3a), For this reason, the Depth Of Discharge, i.e. the amount of energy that can be extracted from a battery, expressed as % of the total battery capacity, is lower when the battery pack is cooled with a velocity of 7 m/s (Figure 3b). Lithium-ion performs better when warm, since heat lowers the internal resistance, but this stresses the battery (Bhatt, 2013): with a velocity equal to 4 m/s the temperature on the battery surface is hotter (Figure 3a) and so the DOD is higher (Figure 3b).

At low air velocity (0, 1.2 and 2.4 m/s) the battery is hotter than using higher air flow rates (4 m/s), but the DOD% is lower (see the highlighted area in Figure 3b), since the tests were stopped earlier for safety reasons, as outlined above.

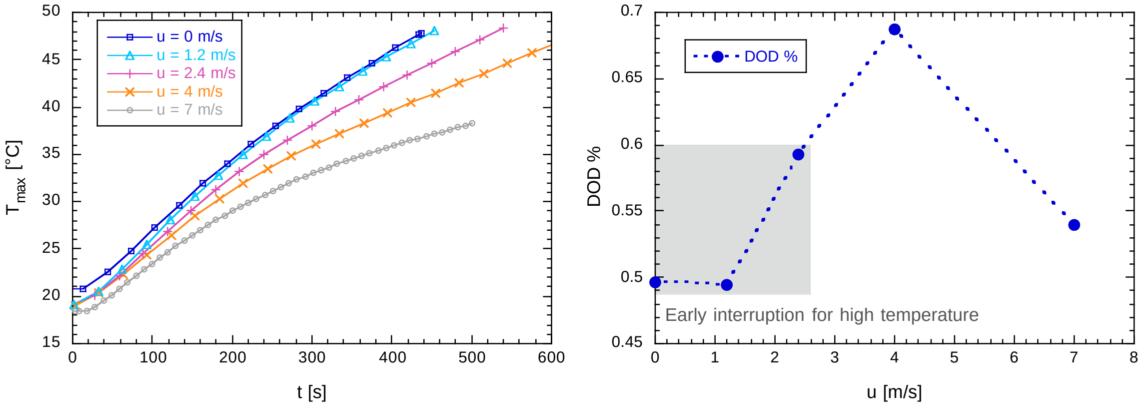


Figure 3: (a) Maximum Temperatures reached on the batteries surface for different air velocities. (b) Discharge capacity of the battery pack for different air velocities.

Maintaining temperature uniformity, within a cell and from cell to cell, is important to achieve the maximum cycle life of cell, module, and pack: the uneven temperature distribution in the battery pack will lead to a localized deterioration and so to a capacity loss of the entire module (Rao et al. 2011).
To analyze the temperature distribution within a cell, the average temperatures at the anode, the cathode and the centre of cells in the battery pack were calculated as average values of all the thermocouples located on each of the three different areas of the four cells connected in series in the module: the temperature trends during the discharge for different air velocities are shown in the graphs below (Figure 4).

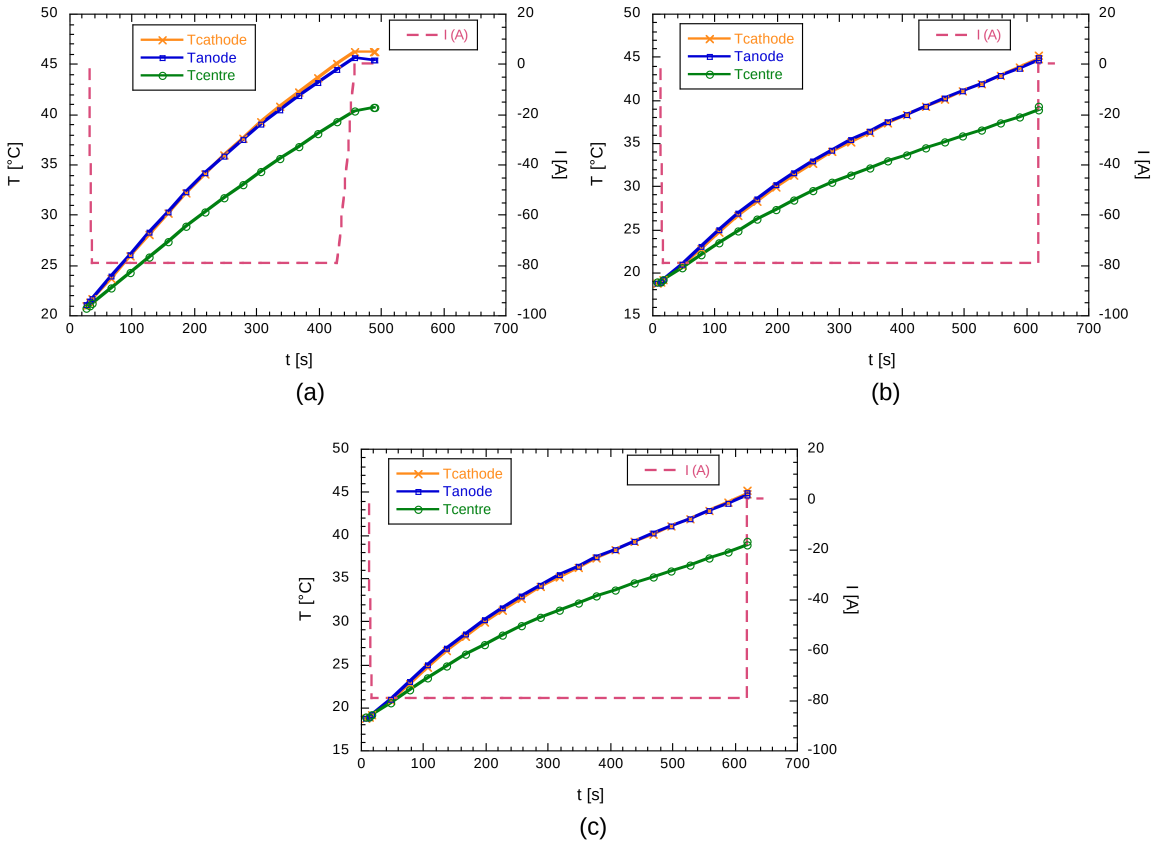
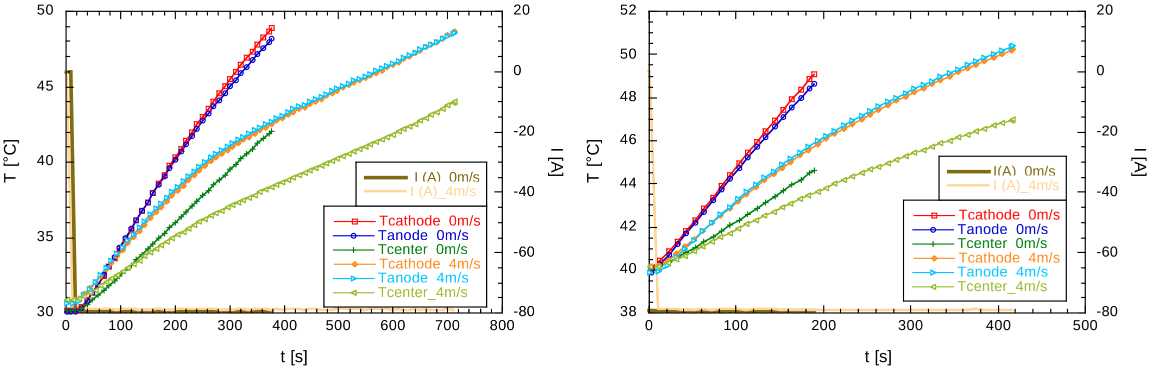


Figure 4: Trend of the average temperatures in different points of the batteries for an air velocity equal to (a) 0m/s (b) 4m/s (c) 7m/s.

Increasing the air velocity, the temperature difference between the centre of the cell and the electrodes decreases. For an air velocity equal to 7 m/s the difference decreases by 3 degrees compared with the case of natural convection, even if it is not possible to reach a uniform temperature on the battery surface.
Additional tests were made using an air velocity equal to 0 and 4 m/s (the minimum velocity to completely discharge the battery at ambient temperature) with an initial temperature of 30°C and 40°C (see Table 2). The results are compared in the graphs below (Figure 5).



(a) (b)

Figure 5: Comparison between the average temperatures at the cathode, anode and the center of the cell for an air velocity equal to 0 and 4 m/s with an initial temperature of (a) 30°C (b) 40°C.

In both cases (T_i = 30°C and T_i = 40°C) with an air velocity equal to 4 m/s the temperature difference between the electrodes and the centre of the cell is reduced by about 2 degrees compared with the case of natural convection (0 m/s).
The depth of discharge of the cell increases, at increasing air velocity: with an air velocity of 4 m/s, for T_i = 30°C the DOD is 48% higher than under natural convection, while for T_i= 40°C the increase is equal to 35%.
To study the temperature distribution inside the battery pack a comparison was made between the temperatures of each battery (the number of the cell in the module is indicated in the legend of the graphs, see Figure 6) in the module at the anode, the cathode and the centre with an air velocity equal to 0 and 4 m/s (tests at ambient temperature are taken as a reference). The results below (Figure 6) show that at increasing air velocity, the temperature at the anode is more uniform in the module. The temperatures were calculated as the average value when the thermocouples are located on both sides of the anode (front and rear) for each cell: (see Figure 2 b). The maximum temperature difference is observed between the third and the first cell in the battery pack: in the case of natural convection ΔT_{max} is 7°C, while with an air velocity of 4m/s ΔT_{max} is 4 degrees (Figure 6).
By increasing the velocity, the temperatures at the centre of the cells and at the cathode do not differ significantly for the batteries in the module.

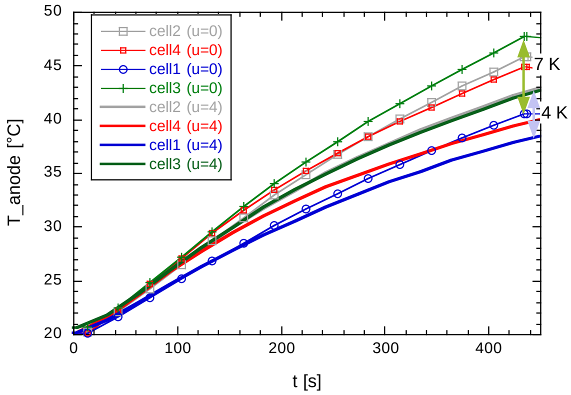


Figure 6: Comparison between the temperatures at the anode of the cell of the four batteries in the module with an air velocity equal to 0 and 4 m/s.

4. Conclusion

The objective of this work was to investigate the heat removal capability of air from a Li-Ion battery pack. It was found that it is actually possible to completely discharge the batteries, without exceeding the maximum allowable temperature for the cells, provided that a minimum air velocity of 4 m/s is adopted; using lower air velocities don't allow to keep the maximum temperature within the safety limits. In particular, this is feasible under laminar flow regime, which is the only practical condition for vehicular applications.

As far as the temperature distribution is concerned, as might be expected, at increasing air velocities, a less apparent temperature gradient is obtained, both within a single cell, and among the different cells of the pack. Nonetheless, under no conditions it is possible to establish a sufficient temperature uniformity within a cell and from cell to cell only using air as cooling fluid

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