Qualitative thermal characterization and cooling of lithium batteries for electric vehicles

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2014 J. Phys.: Conf. Ser. 501 012035
(http://iopscience.iop.org/1742-6596/501/1/012035)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 187.45.240.15
This content was downloaded on 03/07/2016 at 04:59

Please note that terms and conditions apply.
Qualitative thermal characterization and cooling of lithium batteries for electric vehicles

A Mariani1, F D’Annibale1, G Boccardi1, G P Celata2, C Menale3, R Bubbico3 and F Vellucci4

1 ENEA Laboratory of Thermal Fluid-Dynamics Applied to Energy Systems, Italy
2 ENEA, Technical Unit for Advanced Technologies for Energy And Industries, Italy
3 University of Roma “La Sapienza”, Italy
4 ENEA Laboratory of Low Environmental Impact Automotive, Italy

E-mail: mariani_a@enea.it

Abstract. The paper deals with the cooling of batteries. The first step was the thermal characterization of a single cell of the module, which consists in the detection of the thermal field by means of thermographic tests during electric charging and discharging. The purpose was to identify possible critical hot points and to evaluate the cooling demand during the normal operation of an electric car.

After that, a study on the optimal configuration to obtain the flattening of the temperature profile and to avoid hot points was executed. An experimental plant for cooling capacity evaluation of the batteries, using air as cooling fluid, was realized in our laboratory in ENEA Casaccia. The plant is designed to allow testing at different flow rate and temperatures of the cooling air, useful for the assessment of operative thermal limits in different working conditions. Another experimental facility was built to evaluate the thermal behaviour changes with water as cooling fluid. Experimental tests were carried out on the LiFePO4 batteries, under different electric working conditions using the two loops.

In the future, different type of batteries will be tested and the influence of various parameters on the heat transfer will be assessed for possible optimal operative solutions.

1. Introduction

The maturation of the electric car market is strongly influenced by the performance of the energy storage systems. The development of new types of batteries is needed to improve the performance in terms of power and storable energy. In addition, these new types of batteries are required both to increase the reliability and to maintain the same performance for a longer time. In this respect, a key factor is their operating temperature; this value has to remain within a defined range that changes with battery type. Recently this problem has assumed a strategic importance after the inconvenience to the 787e airplane in Japan due, very probably, to an overheating of the lithium battery causing a smoke release in the cabin. The accumulators consist typically of modules constructed by assembling unitary elements (cells); in this configuration, even in a single module there is the possibility of a heat exchange unfavourable condition for some of its elements. Finally, considering that the available space for laying the modules is very limited, an usual situation in an electric car, the importance of an effective system of heat removal becomes very high.

Considering the use of air for battery thermal management may be the simplest approach, and air cooling systems are used for these vehicles because of cost and space limitations. Sun et al. [1]...
developed a three-dimensional thermal model to gain better understanding of thermal behavior of battery cells in a pack cooled with air under simulated driving cycles. The baseline battery pack includes 40 battery units and cooling plates and lower and upper cooling ducts. Simulations indicate that the geometry of cooling ducts can significantly affect the battery temperature uniformity across a pack. In particular, the maximum temperature variation of battery units in a baseline battery pack can be improved by approximately 70% by using a tapered upper cooling duct. However most of the past studies showed that the heat dissipation could not be significantly alleviated by air natural or forced convection, particularly in large-scale batteries. Heat transfer by liquid may be more effective. Heat transfer with liquid could be achieved either through discrete tubing around each module; with a jacket around the module; submerging modules in a dielectric fluid for direct contact; or placing the modules on a liquid heated/cooled plate (heat sink). If the liquid is not in direct contact with modules, such as in tubes or jackets, the heat transfer medium could be water/glycol or even refrigerants, which are common automotive fluids. If modules are submerged in the heat transfer liquid, the liquid must be dielectric, such as silicon-based or mineral oils, to avoid any electrical shorts. However, because of oil’s higher viscosity and associated higher pumping power, a lower flow rate is usually used, making the oil heat transfer coefficient only 1.5 to 3 times higher than with air. Indirect-contact heat transfer liquids such as water or water/glycol solutions generally have lower viscosity and higher thermal conductivity than most oils, resulting in higher heat transfer coefficients. Although liquid cooling/heating is more effective and takes up less volume, it has its drawbacks. It could have more mass, has a potential for leaks, needs more components and could cost more. In an interesting review about power battery thermal energy management by Rao and Wang, it is concluded that at stressful and abuse conditions, especially at high discharge rates and at high operating or ambient temperatures, traditional battery thermal energy management systems, such as air and liquid, may be not meeting the requirements. Pulsating heat pipe may be more effective but needs to be well designed. In addition, progress in developing new high temperature material is very difficult. PCM for battery thermal management is a better selection than others. Nevertheless, thermal conductivity of the PCMs such as paraffin is low and some methods are adopted to enhance the heat transfer of the PCMs. Duan and Naterer used an electric heater to simulate the heat source of a battery cell. Two different PCM designs are investigated: one with a PCM cylinder surrounding the heater, and the other with PCM jackets wrapping the heater. Both configuration exhibit good effectiveness in maintaining the heater within a desired temperature range. Paraffin wax can be encapsulated in the graphite matrix to produce a composite with high thermal conductivity and high latent heat storage. Although many thermal properties of PCMs for battery thermal management are discussed, very little results are available about mechanical properties of these material. For these reasons we decided to test an air thermal management system with electric fans to study the effects of the fluid on the battery block.

2. Preliminary thermographic analysis
The thermal characterization of the single cell was made with a infrared camera coupled with some thermocouples: we are able to see the thermal field on the surface of the cell during charging and discharging electric phases.

The purpose is to identify critical hot points to place the thermocouple. In this manner the maximum temperature will be controlled avoiding the use of the infrared camera. The infrared camera is a FLIR S60, 320x240 pixel sensor and a temperature resolution < 0.1°C. The infrared movies during the transients are taken at constant intervals (from few second to few minutes depending of the supposed velocity of the transient), synchronizing the images obtained from the camera with the data of voltage and current recorded by the cycler. Recording various discharge and charge transient (discharge current from 100 to 500 A), from the thermography of the outer surface, we find the hottest point. This point is located nearby the anode electrode as shown in figure 1. The result in term of temperature are shown in the figures 2-9. In the top graph of each figure the maximum and the mean value of temperature of the external surface are reported, while in bottom graph the value of voltage
and current are reported, the abscissa is the time. The hottest point is about 70°C during the 300 A discharge (figure 5 and figure 6).

**Figure 1** – Typical picture obtained with the infrared camera

**Figure 2.** 100 A discharge for 3850 s, stop 3600 s and 33 A charge

**Figure 3.** 125 A discharge for 3000 s, stop 3600 s and 33 A charge
Figure 4. 200 A discharge for 2000 s, stop 3600 s and 33 A charge

Figure 5. 300 A discharge for 1200 s, stop 3600 s and 33 A charge

Figure 6. same run of figure 5, only discharge

Figure 7. 500 A discharge for 30 s, stop 180 s, 50 A discharge for 5700 s 33 A charge
Figure 8. same run of figure 7, only 500 A discharge for 30 s, stop 180 s and 50 A discharge for 5700 s

Figure 9. same run of figure 7, only 500 A discharge for 30 s and stop 180 s

3 Air cooling
3.1 BA.CO. (BAttery COoling) experimental loop
An experimental plant for cooling capacity evaluation of the batteries, using air as cooling fluid, was realized in the Laboratory of Thermal Fluid-Dynamics Applied to Energy Systems, and the Laboratory of Low Environmental Impact Automotive of ENEA Casaccia. The plant is designed to allow testing at different flow rate and temperatures of the cooling air, useful for the assessment of operative thermal limits in different working conditions. Another experimental facility was built to evaluate the thermal behaviour changes with water as cooling fluid.

3.2 Features demands on BACO:
The loop must cool 4 lithium batteries, the dimension of one battery are 163 x 278 x 51 mm. The electric characteristics are:

- Charge = 100 Ah
- $I_{\text{max}} = 300$ A
- $V_{\text{nom}} = 3.2$ V
- $W_{\text{nom}} = V*I = 960$ W
- Internal resistance = 0.001 $\Omega$

The maximum power to remove with the cooling fluid is:

$$W_{\text{dis}} = R_{\text{f}}I^2 = 90W \quad (9.4\% \text{ of } W_{\text{nom}}) \quad (1)$$

$$W_{f} = 4W_{\text{dis}} = 360W \quad (2)$$

Imposing the air heating up $\Delta T = 2^\circ$C, the mass flow rate is
Using a gap of 1 cm, the passage area is \( A_p = 6480 \text{ mm}^2 \). Using equation 1 the air velocity is:

\[
u = \frac{q}{A_p} = 23.28 \frac{m}{s}
\]  

The pressure drop is (\( f \) calculated from the Pethukov correlation):

\[
\Delta p = f \frac{L \rho u^2}{D^2} = 111 \text{ Pa}
\]

\[
f = (1.82 \log_{10} Re - 1.64)^{-2}
\]  

The power of the fan is calculated using an efficiency \( \eta = 25\% \):

\[
P = Q \Delta p \eta = 67 \text{ W}
\]  

The maximum power in the pre-heater is calculated from equation 1 using \( T_{\text{max}} = 40\^\circ \text{C} \) and \( T_i = 20\^\circ \text{C} \):

\[
W_s = \Gamma_c \rho \Delta T = 3600 \text{ W}
\]  

The heat transfer coefficient is calculated for a \( \Delta T_{\text{wall-fluid}} = 20 \text{ K} \):

\[
q^* = \frac{W_s}{2L} = 1021 \frac{W}{m^2}
\]

\[
h = \frac{q^*}{\Delta T} = 51 \frac{W}{m^2 \text{K}}
\]  

The heat transfer coefficient calculated for the selected geometry vary from 36 \( \text{ W/m}^2\text{K} \) (correlation of Bejan-Krauss, 12) to 70 \( \text{ W/m}^2\text{K} \) (correlation of Gnielinski, 13) and to 101 (correlation of Dittus-Boelter, 14)

The used correlation are reported hereunder:

\[
h = 3.886 \left( \frac{\nu}{L} \right)^{0.5}
\]

\[
\text{Nu} = \frac{f}{8} \frac{Pr(Re-1000)}{1+12.7 \sqrt{f/8(Pr^{2/3}-1)}}
\]  

Using \( f \) from equation (7)

\[
\text{Nu} = 0.023 Re^{0.8} Pr^{0.4}
\]  

In figure 10 is shown the diagram of the experimental loop. The characteristics of the loop are:

- Four axial fans, powered with a 24Vcc ebm-papst 4114NH3;
• An electric pre-heater to assure the desired inlet air temperature;
• An anemometer SCHMIDT ss20.500 to measure the air mass flow rate;
• A channel which length is sufficient to assure a velocity profile completely developed to guarantee a right operation of the anemometer;
• The test section with a thermocouple (to measure the inlet air temperature) and the module (four batteries with a gap of 1 cm and instrumented as shown in Figure 10);
• An air mixing and two thermocouple to measure the outlet mean air temperature;
• The cycler that charge and discharge electrically the module recording the supplied voltage and current;
• The acquisition system, which provides for the registration of the data and the adjustment of the inlet temperature (by controlling the voltage of the heater with a routine PID).

We used four fans mounted in pairs. The channel is a square with insulated panels made in polyurethane coated with aluminium foils. The preheater power is 6,6 Kw. The total length is about 5 m and the internal dimension are 10,6x10,6 cm with a calming length of 2,40 m. The test section is a channel of 30,6x24,4 cm which allows the module. The air passed through the battery in longitudinal sense.

From the result of the previous thermographic campaign we insert the thermocouple in the batteries using 14 thermocouples positioned as shown in figure 11, all the batteries have a thermocouple in the hot point (27 mm under the negative pole) the two central batteries have the thermocouple also in the centre and under the positive pole.

A picture of the test section is in figure 12. During the experimental runs the charge and discharge of the module is done changing the current and measuring the superficial temperature and the heat removed from the air.

**Figure 10.** Diagram of the experimental loop and test section in air cooling
**Figure 10.** Diagram of the experimental loop and test section in air cooling

**Figure 11.** Arrangement of thermocouples on batteries

**Figure 12.** Photo of the module in air cooling loop
3.3 Results of air cooling
To test the batteries we used them in the worst case in charge and discharge. According to data provided by the manufacturer and confirmed by the previous tests, the worst case is when the charge has the value of 1C (a value of current equal to the nominal value of the batteries, 100A for our batteries) and the value of 3C in discharge (300 A), being this parameter the most critical.

So the test has this course: Starting with a completely discharged battery the cycler has a charge at 1C (constant current of 100 A until a tension of 15 V then decreasing tension until 1A, end of charge), after a pause of 60 min the cycler impose a discharge at 3C (constant current of 300 a, until a voltage of 10V, end of discharge)

In this first step we perform limited runs just to evaluate the cooling rate of the various system. For the air cooling we run only with a mass flow rate of 100 m³/h (typical value of low efficiency and reduced dimension fan used in an electric car).

The results are shown in figure 13, for the charge, and figure 14 for the discharge. From the figures we can see that the temperature is well below the limit imposed. (26.5°C during the charge, figure 13, 36°C during the discharge, figure 14). We can say that air could perform properly the function of refrigerant.

4 Water cooling
4.1 Water cooling loop
The water cooling is more complicated than the air cooling due to hazard using an electric device. The good results of the air cooling to maintain the temperature in the operating range suggest us to reduce the number of tests using water as cooling fluid. Therefore the experimental loop was realized in a simplified form. We immerged the module in a pool of water with an adjustable input of water and an output situated at a certain height. This was possible due to the external hermetic housing of the batteries, figure 15. A picture is in figure 16.
The module is the same to the previous one used in the Ba.Co loop, the batteries have a gap of 1 cm. The water input is situated on the bottom of the module to avoid fluctuations in the level and damage batteries. The module is immersed in water up to 1 cm to the electric connectors. The water mass flow rate is regulated by a valve and connected to the domestic line. The water mass flow rate is calculated weighing the waste water in an electronic scale at fixed time and it is constant. The module instrumentation is the same of the air cooling tests.

![Figure 15. Schematic of the experimental loop in water cooling](image)

**Figure 15.** Schematic of the experimental loop in water cooling

![Figure 16. Photo of water cooling loop](image)

**Figure 16.** Photo of water cooling loop

### 4.2 Results of water cooling

For the water cooling the tests are exactly the same of the air cooling. The electric cycle is the same in order of magnitude and timing.

The water mass flow rate is 100 l/h and it is obtained with a little circulation pump which can be easily mounted in an electrical car. The results are shown in figure 17, for the charge, and figure 18 for
the discharge. From the figures we can see that the maximum temperature reached during the charge is 25°C, figure 17, and during the discharge it is 27.5°C, figure 18.

Figure 17. Charge of the module in the water

Figure 18. Discharge of the module in the water

5. Comparison air-water cooling

The results of this comparison are shown in figure 19 for the charge and figure 20 for the discharge. In both figures, the blue lines indicated the temperature recorded by all thermocouples mounted on the battery 1 as shown in figure 11, similarly all the curves relating to the thermocouples respectively mounted on the battery 2, 3 and 4 have been indicated with the green, red and black respectively, (for instance the batteries 1 and 4 are external ones, the batteries 2 and 3 the internal one), always with reference to figure 11.

The analysis of the temperature profiles show that the maximum reached temperature is 25°C in the case of water cooling, 26.5°C in the case of air cooling during the charge, figure 19. These temperatures are well below the limit imposed and we argued that the module can resist to a different charge (es. 1,5÷2C), This fact seems to indicate a good response of this type of batteries to a rapid charge use.

In discharge 3C temperatures are higher: 27.5°C in the case of water cooling, 36°C in the case of air cooling, figure 20. Both cooling systems have proved effective, in fact, the temperatures were well below the limits stated by the manufacturer (+65°C) and above all well below the values recorded in analogous tests carried out at the stage of thermal characterization without cooling. The comparison of efficiency argues in favor of the cooling water.
6. Conclusion

An experimental study was conducted to evaluate the possible cooling of the batteries employed as power supply in the electric car. The first step of this work was to ascertain the presence of hot spots on the single cell of the module used (four batteries linked together). This part was conducted using an infrared camera together with two thermocouples. The hot spot exits and is situated 27 mm under the negative pole. After that two different loops were designed and constructed to cool the module using air and water as cooling fluids. The two system are able to dissipate the heat produced. Obviously the water maintains a lower temperature, but the use of air is preferred because of its greater simplicity and the absence of risks during exercise.

Nomenclature

- $A$: Area [m$^2$]
- $c_p$: specific heat [J/kg K]
- $D$: diameter [m]
- $f_f$: Fanning factor
- $h$: heat transfer coefficient [W/m$^2$K]
- $I$: current [A]
- $k$: thermal conductivity [W/m K]
- $L$: length [m]
- $Nu$: Nusselt number $Nu = \frac{hD}{k}$
- $Pr$: Prandtl number $Pr = \frac{c_p \mu}{k}$
- $q^\prime$': heat flux [W/m$^2$]
- $R$: resistance [Ω]
- $Re$: Reynolds number $Re = \frac{\rho u D}{\mu}$
- $S$: surface [m$^2$]
- $T$: temperature [°C]
- $u$: velocity [m/s]
- $V$: voltage [V]
- $W$: power [W]

Figure 19. Comparison of air-water cooling in charge of the module

Figure 20. Comparison of air-water cooling in discharge of the module in the water
**Greek Symbols**

- $\Gamma$  mass flow rate [kg/s]
- $\mu$  viscosity [N s/m²]
- $\rho$  density [kg/m³]

**References**

[1] Sun H, Wang X, Tossan B and Dixon R 2012 Three-dimensional thermal modeling of a lithium-ion battery pack, *J. of Power Sources* **206** 349–356

[2] Pesaran A A 2001 Battery Thermal Management in EVs and HEVs: Issues and Solutions, *Proc. Advanced Automotive Battery Conference* Las Vegas, Nevada February 6-8

[3] Rao Z and Wang S 2011 A review of power battery thermal energy management, *Renewable and Sustainable Energy Reviews* **15** 4554–4571

[4] Duan X and Naterer G F 2010 Heat transfer in phase change materials for thermal management of electric vehicle battery module, *Int. J. of Heat and Mass Transfer* **53** 5176–5182

[5] Kizilel R, Sabbaha R, Selmana J R and Al-Hallaj S 2009 An alternative cooling system to enhance the safety of Li-ion battery packs, *J. of Power Sources* **194** 1105–1112