STUDIES CONCERNING LI-ION BATTERY THERMAL BEHAVIOUR IN LOW TEMPERATURE ENVIRONMENT

Ing. Adriana TRAISTARU
Continental Automotive Romania S.R.L.,
Str. Siemens 1, 300704 Timisoara, Romania, Tel. +40-256-251084, E-mail: Adriana.Traistaru@continental-corporation.com

Prof. dr. ing. Ioan SORA
"Politehnica" University of Timisoara, Faculty of Electrical and Power Engineering
Bd. V. Parvan 2, 300223 Timisoara, Romania, Tel. +40-256-403446, E-mail: ioan.sora@et.upt.ro

Abstract: *A solution for heating up a Li-ion cell and a thermal model for a Li-ion cell is presented into this paper. The model is capable of predicting the cell internal temperature space distribution and its evolution in time during battery heat up process. The cell temperature influences the cell behaviour. Batteries suppliers recommend temperatures for Li-ion batteries between -20^{0}C and 60^{0}C. When the battery temperature is lower than -20^{0}C, the battery cannot supply any current. In low temperature environment (below -20^{0}C) the battery shall be heated up in order to bring it into proper temperature range.*

Keywords: *Li-ion battery thermal model, thermal field distribution, battery heat up process.*

1. Introduction

Performance and safety are two primary considerations in the design of advanced lithium-ion batteries. The performance of a lithium-ion battery can be greatly influenced by the thermal environment, and its thermal behavior is in turn determined by the electrochemical and chemical processes occurring inside the cell during charge and discharge [1].

Li-ion batteries are used as backup energy supply for an electronic brake system for cars. Taking into consideration that the brake system of the car is a safety critical application, battery management system shall ensure that this brake system is permanently supplied from an electrical energy source. The Li-ion technology was chosen as backup energy supply device for this type of braking system. The temperature range for this type of battery is between -20^{0}C and +60^{0}C. The temperature range for the cars is usual between -40^{0}C and +85^{0}C. Battery thermal management shall ensure that the backup batteries are operational over the entire car temperature range. This paper proposes a solution for heat up the battery in cases when the temperatures are below -10^{0}C. A modeling of thermal field distribution inside the battery is also presented. For the safety reasons the temperature in any part of the battery shall not be above 60^{0}C and also the temperature gradient inside the battery shall be as low as possible during heating process [6].

The battery must be equipped with a heating system to match the required load pattern. Thus, at low temperatures at which the battery does not match the required load pattern, a vehicle cannot start until the battery has reached a temperature at which it matches the required pattern.

Two different heating systems are possible: external heater – which heats up the battery over an external power supply (vehicle power net) and internal heater – which heat up the battery by discharging the battery (power dissipation over the internal resistance of the battery increases the battery temperature).

This results in the following requirements for each heating system [4]:

For external heater:

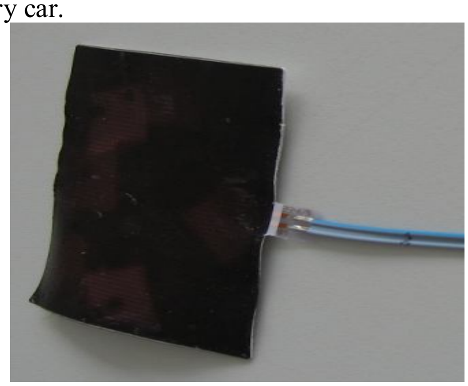
- heating the battery from -40^{0}C (lowest temperature) to a temperature at which it matches the load pattern within 2 minutes;
- employment of self-regulating heating elements to prevent the battery exceeding its maximum temperature in case of a failure;
- providing homogenous temperature distribution to prevent hot spots which would cause accelerated ageing of the battery;
- providing an electronic system to activate the heating system at negative temperatures and to automatically turn it off at temperatures over 10^0 C;

- feeding battery heater via the vehicle supply system and activation only with an energy source available;

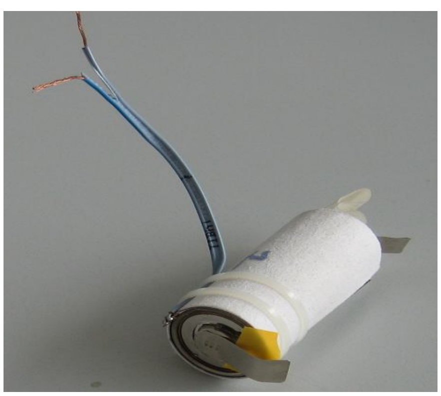
For internal heater:

- heating the battery from -40^0C to a temperature at which it matches the load pattern within 2 minutes;
- battery technology must be able to provide sufficiently high discharge currents at -40^0C to use the high battery resistance as a heater;
- providing an electronic system to discharge the battery at negative temperatures and to automatically turn off the discharging at temperatures over -10^0C.

Because this project works with Sony Li-ion 26650 batteries that cannot supply any current for -40^0C temperature, the solution with external heating device was chosen [5]. There is a heating foil – see Fig.1 – which is supplied with energy from lead-acid battery car.



a



b

Fig. 1 a. Heating foil for one cell; b. Li-ion cell equipped with heating foil

2. Theoretical considerations

The basic cell chemistry and design are the same for all types of Li-ion automotive cells. Fig. 2 shows a typical Li-ion cell design. Thin layers of cathode, separator, and anode are rolled up on a central mandrel and inserted into a cylindrical can. The gaps are filled with liquid electrolyte. The basic design remains unchanged on substitution of one electrode material for another, although the layer thicknesses might change [3]. This is the same design used for most small commercial cells.

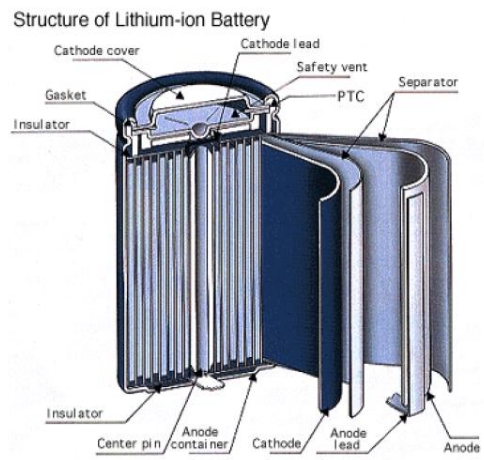
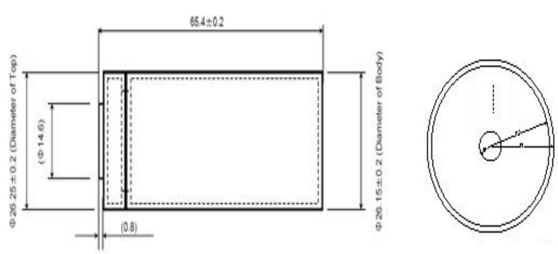


Fig. 2 Internal structure of Li-ion cylindrical battery

The battery data from the battery manufacturer are as follows: nominal voltage: 3.6 [V]; nominal capacity: 2.5 [Ah] –for a discharge current 0.2C (1C=2.5[A], 0.2C=0.5[A]); maximum charge voltage: 4.1 [V]; cells shape: cylindrical; geometrical data: diameter: 26 [mm], height: 65 [mm]; mass: 89.5 [g]; heat capacity : 900[J/(kg*grd)] - global value. In Fig.3 the cell geometrical data and cell space discretisation can be seen:



a. *b.*

Fig. 3 a. Cell geometrical data; b. Space discretisation for one transversal section

For the calculation of thermal field distribution over the cell section, the cell is considered homogeneous inside. The Fourier equation for the heat up process of the cell using external heating foils is [2]:

$$\frac{\partial \vartheta}{\partial t} = a\Delta\vartheta \qquad (1)$$

Where: $a = \frac{\lambda}{\rho' c} \left[\frac{m^2}{s}\right]$ - global thermal diffusion of the cell;

$\lambda\, [\frac{W}{m * grd}]$ – global thermal conductivity of the cell;

$\rho'\, [\frac{kg}{m^3}]$ – global density of the cell;

c$[\frac{J}{kg * grd}]$ – global heat capacity of the cell;

ϑ [K] – temperature;

For the cylindrical shapes the Fourier equation (1) becomes:

$$\frac{\partial \vartheta}{\partial t} = a\left(\frac{\partial^2 \vartheta}{\partial r^2} + \frac{1}{r}\frac{\partial \vartheta}{\partial r}\right) \qquad (2)$$

Where ***r*** means the radius and ***t*** means time.

For solving this equation some other data and conditions are necessary to be specified.

Initial conditions for the cell heat up process: the initial temperature inside the cell is the same over the entire section and its value is equal with the cell surface temperature.

Boundary conditions for the cell heat up process: the cell surface temperature is known during heat up process $\vartheta_s = \vartheta_s(t)$;

For solving the equation (2) finite difference method is used. For the left part of the relation (2) it could be written:

$$\frac{\partial \vartheta}{\partial t} = \frac{\vartheta^{(k)} - \vartheta^{(k-1)}}{t_k - t_{k-1}} \qquad (3)$$

$\Delta t = t_k - t_{k-1}$ - time step = 1 [s] (4)

$\vartheta^{(k)}$ - temperature value at the actual moment (*k* moment);

$\vartheta^{(k-1)}$ - temperature value at the previous moment (*k-1* moment);

For the right part of the relation (2):

$$\frac{\partial \vartheta}{\partial r} = \frac{\vartheta_{i-1} - \vartheta_i}{r_{i-1} - r_i}, \quad i=1...13 \qquad (5)$$

$\Delta r = r_{i-1} - r_i$ - spatial step = 1[mm] (6)

$$\frac{\partial^2 \vartheta}{\partial r^2} = \frac{\vartheta_{i-2} - 2 * \vartheta_{i-1} + \vartheta_i}{\Delta r^2} \qquad (7)$$

Relation (2) becomes:

$$\frac{\vartheta_i^{(k)} - \vartheta_i^{(k-1)}}{\Delta t} = a * \left(\frac{\vartheta_{i-2}^{(k)} - 2 * \vartheta_{i-1}^{(k)} + \vartheta_i^{(k)}}{\Delta r^2} + \frac{1}{r_i} * \frac{\vartheta_{i-1}^{(k)} - \vartheta_i^{(k)}}{\Delta r}\right) \qquad (8)$$

The temperature of *i* layer at actual moment of time – *k* – is calculated with following relation:

$$\vartheta_i^{(k)} = \frac{1}{1 - a * \Delta t * \frac{r_i - \Delta r}{r_i * \Delta r^2}} * \left[\vartheta_i^{(k-1)} + \frac{a * \Delta t}{r_i * \Delta r^2} * \left(\vartheta_{i-2}^{(k)} * r_i - \vartheta_{i-1}^{(k)}(2 * r_i - \Delta r)\right)\right] \qquad (9)$$

Another simplifier hypothesis is concerning thermal distribution along the height of the cell. Temperature is considered constant along the height of the cell for the same radius. The temperature of the cell depends on the radius during the heat up process with external heating foil and also depends on time.

3. Thermal modeling of Li-ion cell

Taking into consideration the available data of the cell:

- global density: $\rho = 2.525*10^3$ [kg/m^3];
- global heat capacity: *c* = 900 [J/(kg*grd)];
- global thermal conductivity: λ = 0.575 [W/(m*grd)];

and geometrical data specified before, a model using Matlab/Simulink tool with Simscape library is developed. One layer – which is 1 mm thick –is modeled in Matlab/Simulink from the thermal point of view and it looks like in Fig.4:

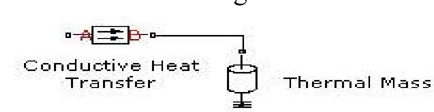


Fig.4 Thermal modeling for 1 layer of the cell

For each layer the volume and external surface is calculated. In Fig.5 thermal model for the entire cell is presented.

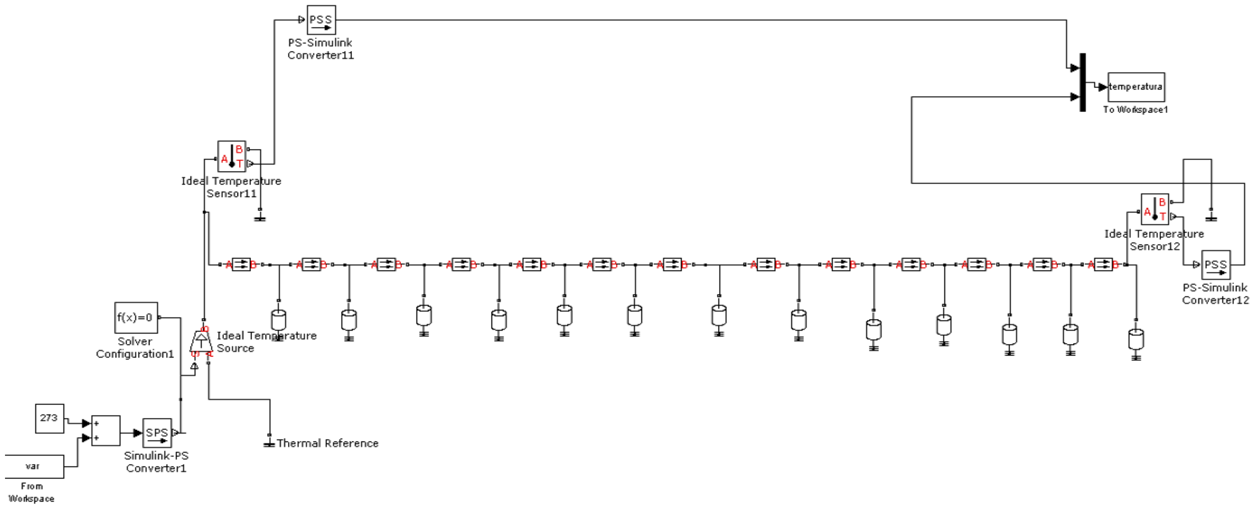


Fig. 5 Thermal modeling of entire cell using Matlab/Simulink

4. Verification and conclusion

In order to verify the thermal model of the cell, one cell SONY 26650 was equipped with one thermocouple inside the cell, in the middle, and another one on the cell surface, as it could be seen in Fig.6:

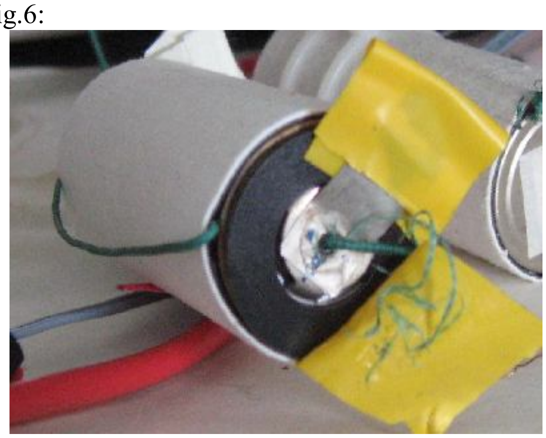


Fig. 6 SONY 26650 cell equipped with thermocouples

Starting at -40^{0}C (233K) environment temperature the cell was heat up during 120 seconds– it is a system requirement – using external heating foil. The measured data and simulation results could be seen in Fig.7. At the end of the heat up process the temperature on the cell surface is 32 ^{0}C (305K).

In Fig. 7 are presented the curves for temperature distribution for the surface and middle point of the cell during heat up process. As input data for the thermal model of the cell the measured data for cell surface temperature are given. It could be seen in Fig.7 that the temperature values in the middle of the cell for the measured data and for simulation results are in very good correlation. Taking into consideration the simulation results and measured data, after 2 minutes the temperature in the middle of the cell is around 250K (-23 ^{0}C). It supposes that the cell is able to provide discharge current after 2 minutes heating time with external heating foils.

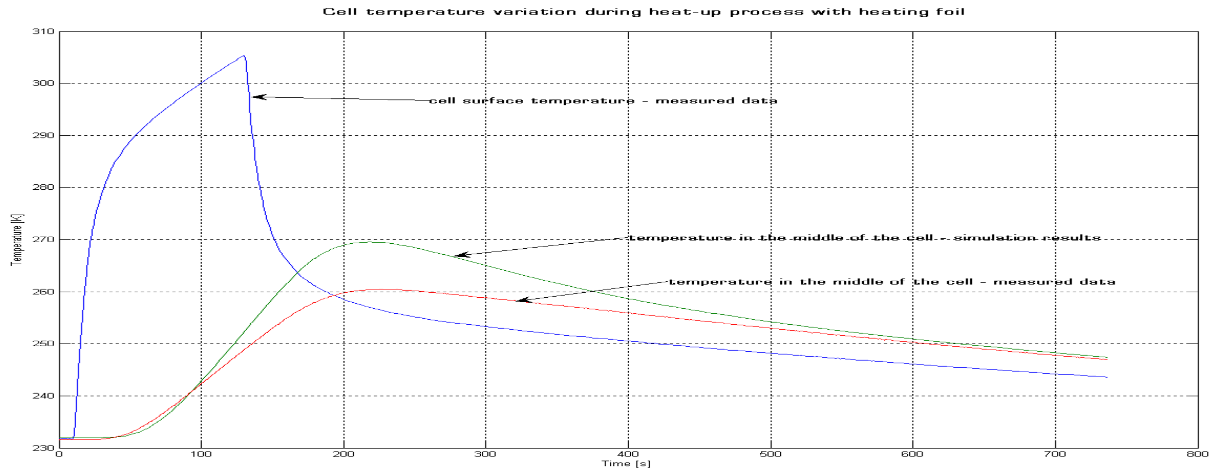


Fig. 7 Temperature distribution inside the cell during 120 seconds heating time

In order to verify this hypothesis, another Li-ion 26650 Sony cell was introduced into thermal chamber. This second cell is equipped with the same type of heating foil as first one and it was heated simultaneously as the cell equipped with thermocouple inside. Both cells are kept in the same temperature condition into thermal chamber. In Fig.8 both cells can be seen into thermal chamber Votsch 4002.

Fig.8 Two cells into thermal chamber Votsch 4002

Both cells were cooled down to -40^{0}C and kept at -40^{0}C until the temperature inside them was homogeneous. After that the heating procedure for 120 [s] was started simultaneously. After 120 [s] heating time a discharge procedure with current corresponding to 2 brake cycles was performed from second cell. The current profile for one brake cycle is presented in Fig.9:

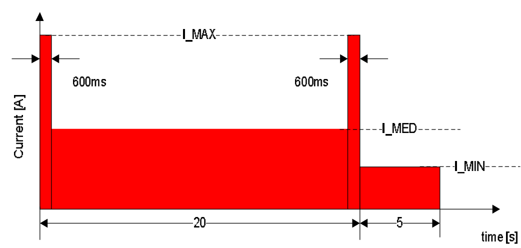


Fig.9 Current profile for one brake cycle

The voltage and current curves during discharge procedure can be seen in Fig.10:

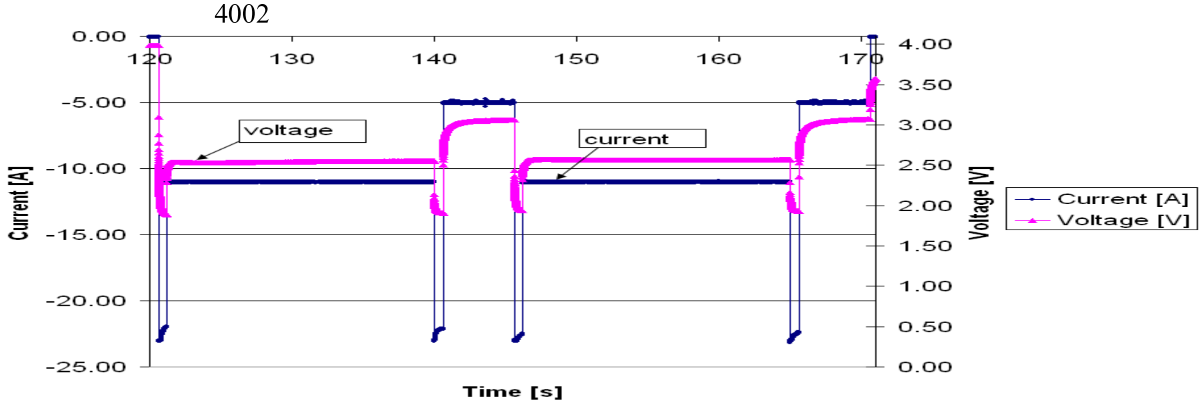


Fig.10 Battery voltage and current during discharging with 2 brake cycles after 120 [s] heating time

The test results shows that after 120 [s] heating time, initial battery temperature -40^{0}C, the battery is not able to provide the power needed by the brake cycles. The battery cannot provide the maximum discharge current 23 [A] during 600 ms discharging time. That means that the heating procedure shall continue in order to bring the cell into proper temperature range. For the second test scenario the heating procedure was continued until the temperature inside the cell reached -20^{0}C. When this temperature was reached, the discharge procedure with 2 brake cycles was performed. The temperature curves and the battery voltage and current curves are shown in Fig. 11 and 12:

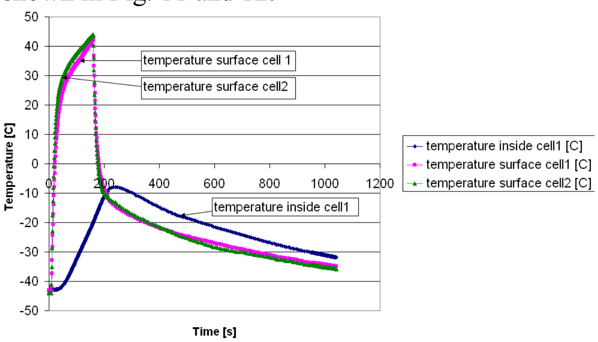


Fig. 11 Cells temperature during heat up process

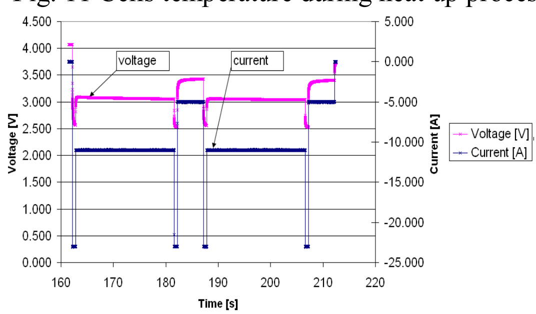


Fig. 12 Battery voltage and current curves during discharging with 2 brake cycles after heat up process

It could be seen in Fig.11 that the temperature inside the cell is -20^{0}C after approximately 160 [s] since the heat up process began. The discharged battery was the second one which is equipped with one thermocouple on the surface. Prescribed brake cycles can be seen in Fig.12: the battery is able to provide the power needed by the application. During discharging with 23 [A] for 600 [ms] current the battery voltage drops to approximately 2.5[V].

In conclusion, the battery shall be heated up with heating foil for 160 [s] in order to be able to provide the energy with the parameters which are required by the electric brake system. If it is heated up just 120 [s] it is not able to provide the brake cycles current profile.

The temperature gradient inside the cell could also be a problem. It should be verified along life time of the cell how this parameter influences the ageing of the cell.

The cell suppliers didn't offer any figure for the maximum temperature gradient inside the battery, the fact is that this gradient shall be kept as low as possible. Maybe a longer time for the heating process would have better results from the cell ageing point of view. This aspect will be studied further in time.

References

1. Bergveld H.J., Kruijt W.S. and Notten P.H.L., *Battery Management Systems – Design by Modeling*, Kluwer Academic Publishers, 2002.
2. Sora I., Golovanov N, ş.a., *Electrotermie şi electrotehnologii (Electrothermics and Electrotechnologies)*, vol.I, Editura Tehnica, 1997
3. Linden D., Reddy T.B., *Handbook of Batteries*, third edition, McGraw-Hill, 2002;
4. Pesaran A, *Battery Thermal Management in EVs and HEVs: Issues and Solutions*, Advanced Automotive Battery Conference, 2001;
5. Traistaru A., *Diagnosis of Li-ion Batteries Used for Power Application in the Automotive Industry* Proceedings of the 8th European Symposium on Electrochemical Engineering, pp. 194–208, Prague 2008.
6. Traistaru A., *Li-ion Battery Management Concept for Dry-by-wire Systems, International Automotive Electronics Congress*, Proceedings of the International Automotive Electronics Congress, Paris 2008.