Analysis of the thermal behavior of a LiFePO$_4$ battery cell

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Abstract.
This paper presents theory, experiments and numerical modeling results for the electro-thermal analysis of Lithium Iron Phosphate (LiFePO$_4$) battery cells. Thermal management of batteries is important for several reasons including thermal runaway and maintaining battery operating time. A battery pack is comprised of battery cells which are stacked together without cooling surfaces except for the pack outer surface. The central cells in the pack are therefore exposed to the risk of overheating.

A model for a single specific commercial LiFePO$_4$ battery cell is presented together with preliminary experiments and results for determination of heating sources during charging and discharging. Based on the experimental results we extract model parameters for use in the model. The experiments lead to relations for the cell surface temperature and the lump temperature of the cell. A reasonable agreement between experiments and the model is found and suggestions for further work is indicated.

1. Introduction
Lithium-Iron-Phosphate (LiFePO$_4$) batteries are becoming a preferred choice of energy storage for electric vehicles in the fast development of this field. They are claimed to provide higher voltages, more capacity and cycle life at reduced weight[1]. However, the use of these batteries is challenging due to high heat generation during operation. In addition the performance and lifetime are again sensitive to the temperature and the rated operating range for such batteries is relatively narrow. The lifespan of the Li-ion cell is reduced by about two months for every degree of temperature rise in an operating temperature range of 30 − 40 °C[2]. As a result the Li-ion battery system should maintain the maximum cell temperature below 40 °C and the temperature difference between the battery cells contained in a battery pack below 5 °C for a full life span[3]. Thus, careful thermal management of electric vehicles battery-packs using this battery technology is required in order to maintain performance and lifetime.

The conventional solution to thermal management is usually accomplished by temperature sensors included in the battery management system (BMS), where batteries are shut down when critical temperatures are reached. The use of active cooling by forcing the circulation of air or liquid can improve the battery performance by 30 − 40 %[4, 5]. Mahamud[6] made a numerical analysis of a thermal management method using a reciprocating air flow for cylindrical Li-ion cells. His results showed a 4 °C decrease in the temperature difference in the battery pack and
also a 1.5 °C decrease in the maximum cell temperature for a reciprocating period of 120 s.

Another possibility for thermal control is the use of a phase-change-material (PCM) incorporated in the battery module to create a passive thermal system. With a simple design that should be much cheaper to implement than an active cooling system[7, 8, 9]. Khateeb et al.[10] used aluminum foam and fins to increase the poor thermal conductivity of the PCM. Furthermore they used a simplified unsteady-state two-dimensional thermal model to simulate Li-ion battery operation for an electric scooter which was experimentally validated[11].

The purpose of this project is to analyze the thermal management of an electric battery used to power the press of a refuse truck. Especially we want to devise an efficient thermal system to maintain the battery temperature in a certain interval in which the life span and storage capacity are not reduced beyond a certain limit.

The battery cell used in this study was a China Aviation Lithium Battery model SE70AHA having a nominal capacity and voltage of 70 Ah and 3.2 V, respectively. A cross section through a quarter of the cell is depicted in Figure 1. The internal structure and the transverse thermal resistance network used in the mathematical model are indicated. The information regarding the geometry of the cell is summarized in Table 1.

2. Experimental setup

The aim of the experiment was to measure the temperature as a function of the charge/discharge current, position and time. This was done using the experimental setup shown in Figure 2. It consisted of a thermal camera FLIR i60 (a), a climate chamber Welltec (b) with an internal fan and an operating range of −30 to 120 °C, used to keep the battery cell (c) at a constant temperature. A laboratory power supply PS-9080-100 (d) with an operating range of 0 − 80V / 0 − 100A was used for charging the battery cell at a constant current/voltage.
Table 1. Information about the geometry of the battery cell.

|                              |                  |
|------------------------------|------------------|
| Size of battery (L × w × h)  | 115 mm × 61 mm × 203 mm |
| Size of a pouch cell (L × w × h) | 100 mm × 0.272 mm × 165 mm |
| Size of the pouch cells area (L × w × h) | 100 mm × 49 mm × 165 mm |
| Thickness of the HDPE case    | 4 mm             |
| Thickness of the exterior polyethylene layer | 0.303 mm |
| Thickness of the PP separator | 0.036 mm         |
| Thickness of carbonaceous electrode | 0.067 mm |
| Thickness of copper foil      | 0.026 mm         |
| Thickness of lithium electrode | 0.079 mm         |
| Thickness of aluminum foil    | 0.064 mm         |

and an electronic load EL 3000/800/100 INT 2E (e) with an operating range of 2.5 – 800V / 0.01 – 100A was used to discharge the battery cell at a constant current. A data acquisition switch unit AGILENT 34970A (f) interfaced with a personal computer (g) was used to measure the voltage of the battery cell during the charge/discharge process using two sensors placed on the battery cell’s poles. Finally, a four channel data logger thermometer ELMA 718 (h) interfaced with K-type thermocouples (i) was used to measure the temperature of the battery cell.

Figure 2. Experimental setup.

The thermal camera was used to measure the surface temperature profile of the battery cell. This allowed visual determination of the spatial temperature distribution. During the experiments the climate chamber was used to maintain the temperature at a constant level, so the battery cell was cooled using forced convection. The door of the climatic chamber was left open and a board of Poly methyl methacrylate - Plexiglas was placed instead. Through this board, a hole with diameter equal to the diameter of the thermal camera’s objective was made to enable the data collection. To reduce heat transfer through the hole, the temperature in the climate chamber was set equal to the temperature inside the laboratory. Thermal pictures of
the battery cell were made in every one minute during the experiments. The thermal camera was used during the following experiments:

- charging the cell at constant current using 14, 18, 35A;
- discharging the cell at constant current using 14, 35, 70A.

The data logger interfaced with 4 K-type thermocouples was used to measure the surface temperature as a function of the charge/discharge current and time. Experiments were made using the climate chamber to maintain the temperature at a value of 25°C and actively cooling the cell. The same values for the charge/discharge current as for thermal camera experiments were used. Figure 3 shows a top view of the battery cell in which (a) and (b) are the positive and the negative battery poles, (c) is the battery cell vent and T1, T2, T3 and T4 are K-type thermocouples. These thermocouples were 3 m long and had a wire diameter of 1.5 mm.

![Figure 3. Top view of the battery cell with the placement of the thermocouples.](image)

3. Model Description

A numerical model of the battery cell having as components the pouch cells, the air gap in the upper part and the plastic casing was developed. The lithium-ion batteries have a porous structure for the electrodes and separators so the liquid electrolytes are trapped inside them. Because of the little mobility of the fluids, heat convection inside the pouch cell can be neglected. In the same manner, due to the enclosed and opaque structure of the battery cell, the heat transfer rate through radiation can also be neglected.[12]

Heat conduction is the predominant heat transfer phenomenon taking place inside the battery cell and the energy conservation reads:

$$\rho C_p \frac{\partial T}{\partial t} = k_{\text{long}} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) + k_{\text{trans}} \frac{\partial^2 T}{\partial y^2} + \dot{q},$$

where \( \rho \), \( C_p \), \( \dot{q} \) represent the density, heat capacity and heat-generation rate per unit volume, respectively. Furthermore we have assumed that the thermal conductivity \( k \) can be decomposed into a longitudinal (\( x, z \)) and a transverse (\( y \)) component.

The product value of density, heat capacity and the thermal conductivities for the pouch cells domain are calculated through:

$$\rho C_p = \frac{\sum_i \rho_i C_{p,i} V_i}{\sum_i V_i}, \quad k_{\text{long}} = \frac{\sum_i k_i A_i}{\sum_i A_i}, \quad k_{\text{trans}} = \frac{\sum_i L_i}{\sum_i \frac{L_i}{k_i}},$$

where \( V_i \), \( L_i \) and \( A_i \) are the volume, thickness and transverse area of each material \( i \), respectively. The thermal and physical properties of each material are listed in Table 2.
Table 2. Thermal and physical properties of each material used in the mathematical model.

| Material             | Density ($kg m^{-3}$) | Heat Capacity ($J kg^{-1} K^{-1}$) | Thermal conductivity ($W m^{-1} K^{-1}$) | Emissivity |
|----------------------|-----------------------|------------------------------------|----------------------------------------|------------|
| Carbonaceous electrode | 1347.33               | 1437.4                             | 1.04                                   |            |
| Lithium electrode    | 2328.5                | 1269.21                            | 1.58                                   |            |
| Al foil              | 2702                  | 903                                | 238                                    |            |
| Cu foil              | 8933                  | 385                                | 398                                    |            |
| PP separator         | 1008.98               | 1978.16                            | 0.3344                                 |            |
| HDPE case            | 950*                  | 1886*                              | 0.42*                                  | 0.9*       |

The values used for the material properties are from [12] except for * which are from [13].

In the solution of the energy equation for the domain (8) in Figure 1 we will only consider the heat transfer through an effective conduction coefficient and not solve for the flow of the air. Thus, the air gap in the upper part of the battery cell is treated as a horizontal enclosure having the hot plate at the bottom part[14]. The Rayleigh number for this enclosure is:

$$Ra = \frac{g\beta (T_1 - T_2)}{\nu^3} L^3 Pr,$$

(3)

where the characteristic length $L_c$ is the distance between the hot and cold surfaces, $T_1$ and $T_2$ are temperatures of the hot and cold surfaces, $g$ is the gravitational acceleration and $\beta$, $\nu$ and $Pr$ are air’s coefficient of volume expansion, kinematic viscosity and Prandtl number evaluated at the average temperature of the fluid $T_{ave} = \frac{(T_1 + T_2)}{2}$, respectively. The convection heat transfer in an enclosure is analogous to the heat conduction across the fluid layer in the enclosure provided that the thermal conductivity $k$ is replaced by $k_{eff} = kNu$. For horizontal enclosures that contain air, Hollands et al[15] recommend the correlation:

$$Nu = 1 + 1.44 \left( 1 - \frac{1708}{Ra} \right)^+ + \left( \frac{Ra^{1/3}}{18} - 1 \right)^+, \quad Ra < 10^8,$$

(4)

where the notation $( )^+$ indicates that if the quantity in the bracket is negative, it should be set equal to zero.

The battery cell was tested inside a climate chamber which kept a constant temperature through forced convection. The convective heat transfer is used as a boundary condition according to the formula:

$$\dot{Q}_c = h_c (T_s - T_\infty),$$

(5)

where $h_c$, $T_s$, $T_\infty$ represent the convective heat transfer coefficient, surface temperature and ambient temperature, respectively. The convective heat transfer coefficient is calculated through a conventional Nusselt number correlation, where $L$ is the length battery cell and $Nu_{cyl}$ is the Nusselt number for a non-circular cylindrical body in cross flux with a square cross-section[16]:

$$Nu_{cyl} = \frac{h_c L}{k} = 0.102Re^{0.675}Pr^{1/3}, \quad 5000 < Re < 100000.$$

(6)

Radiative heat transfer at the boundary is also taken into consideration according to the formula:

$$\dot{Q}_r = \epsilon \sigma (T_s^4 - T_\infty^4),$$

(7)

where $\epsilon$ and $\sigma$ represent the surface emissivity and the Stefan-Boltzmann constant, respectively. Based on experimental measurements, it was estimated that the convective and radiative heat
transfer rates represent 73% and 27%, respectively, of the total heat transfer rate to the environment.

In lithium-ion battery cells the heat generation rate was derived by Thomas and Newman [17]. We adopted the approach of [18] and used the following simplified formula:

$$\dot{q} = \frac{1}{V_{\text{total}}} \left[ I \left( E - U^{\text{avg}} \right) + IT \frac{\partial U^{\text{avg}}}{\partial T} \right],$$  \hspace{1cm} (8)

where $V_{\text{total}}$ is the total volume of the pouch cells, $I$ is the current (positive for a charge process) $E$ is the cell voltage, $U$ is the equilibrium potential and $T$ is the temperature. The values for the equilibrium potential were determined experimentally as the open-circuit voltages for each state of charge [19] and the ones for $\frac{\partial U^{\text{avg}}}{\partial T}$ were taken from [18]. The first term represents the heat generated due to the electric resistance of the cell and it is always positive. On the other hand the second term, that represents the reversible entropic heat, can be either positive or negative. For a complete charge + discharge cycle this term is equal to zero.

The model constituted by equations (1 – 8) is solved using the Comsol finite element solver.

4. Results and comparison

When the cell is being charged/discharged using a current value less than 18A, (the recommended value for charging the cell given by the producer) the temperature profile is nearly uniform. This is seen in Figure 4, where (a) represents the cell measured temperature profile and (b) represents the temperature profile obtained from the simulation. The discharge current was 14 A, the simulation/discharge time was 16820 s and the temperature in the climate chamber was 30.2°C. The maximum surface temperature measured during the experiment was 32.1°C and the model gave a maximum temperature of 33.5°C.

For currents of 35A or higher used to charge/discharge the cell, the temperature profile is not uniform. The surface temperature in the middle region of the cell has a high increase and also hot spots appeared. This can be seen in Figure 5 that was obtained for a discharge current of 70 A and a discharge/simulation time of 3140 s. The maximum temperature given by the mathematical model was 39.4°C while the measured value was 39.8°C.

![Figure 4](image-url) \hspace{1cm} ![Figure 5](image-url)

(a) experiment \hspace{1cm} (b) simulation

Figure 4. The battery cell surface temperature distribution after discharging at 14A.
In Figure 6 the surface temperature variation measured by the thermocouple T1 is compared to the one obtained from the model for a discharge current of 70 A and a simulation time of 4090 s. The measured variation of the battery cell voltage was added to underline the connection between it and the heat-generation. It can be seen that in the end of the discharge process the temperature has a fast increase. This happens because of the high values of the heat generation term that appear in the end of the discharge process, when the difference between the voltage and equilibrium potential increases dramatically and the temperature term \( \frac{\partial U_{avg}}{\partial T} \) reaches its maximum\(^{[19]} \). The measured and simulated temperatures reached a maximum of 34.1 °C and 36.1 °C, respectively. This difference is attributed to imperfect geometry of the battery cell, to the imperfect contact between the cell and the thermocouple that was obtained by using a resin...
and to the constant value of the convective heat transfer coefficient used in the simulations.

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6. Conclusions

A three-dimensional electro-thermal model was developed to simulate the behavior of a LiFePO$_4$ battery cell. The values for the thermal and physical properties of the materials used in the model were taken from literature and no tweaking of parameters was performed. The results show a good match between the simulations and the experimental measurements. This study is the initial step in implementing a thermal model for a complete battery pack.

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