A Transient, Non–Isothermal, Fully Coupled Model for Predicting the Potenial Drop, Temperature Distribution and Corrosion Rate in Lead–Acid Battery Grids

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Abstract

The temperature distribution in the lead-acid batteries during charging and discharging process has a significant effect on the potential drop and efficiency of the battery. To study this phenomenon, a two-dimensional model has been developed to predict non-isothermal transient behavior of the lead-acid batteries during charging and discharging cycles. The model is based on applying the conservation laws for the current and heat transfer to the positive and negative grids. The system of the governing equations is fully coupled and should be solved iteratively. A finite volume method is employed to discretize the governing differential equations whose solutions are temperature, voltage and current distribution on the positive and negative electrodes. The results show that with increasing the temperature during discharging cycle the potential drop increases compared to prediction of the isothermal model. The proposed model is useful for a more realistic behavior prediction of the lead-acid batteries.

1 Introduction

During the previous decades, a vast amount of research has been devoted to develop methods for reducing the losses in the battery grids [1-4]. Historically, the models for potential drop have been developed with different point of view i. e. the wire model and differential model [5]. Also, the thermal behavior of lead-acid battery has been investigated by many researchers [6-12].

In the present study, a 2D transient and non-isothermal model are presented that can predict the potential drop, temperature distribution and corrosion in positive and negative plates. The transient differential equations for the potential drop and heat transfer are coupled due to the fact that the current density which appears as a source term in the equation of the potential drop is itself a function of the temperature distribution. Moreover, the corrosion rate of the battery grid is a function of the voltage and temperature distribution in the electrode. The model can be used to study the effects of design and operating parameters. It could be also used to design more powerful batteries for the EV applications.

2 Mathematical Model

Applying Ohm's law for a control volume on a battery grid results into:

$$\frac{\partial V_i}{\partial t} = \frac{\partial}{\partial x}(\sigma \frac{\partial V_i}{\partial x}) + \frac{\partial}{\partial y}(\sigma \frac{\partial V_i}{\partial y}) + J_i \tag{1}$$

where, V is the potential, σ is the effective conductance, J is the current density, and the subscript i denotes either the positive or negative electrodes. The equation governing the temperature distribution is given by [12]:

$$(\rho c_p)_i \frac{\partial T_i}{\partial t} = \lambda_i \nabla^2 T_i + q_i(T_i) \tag{2}$$

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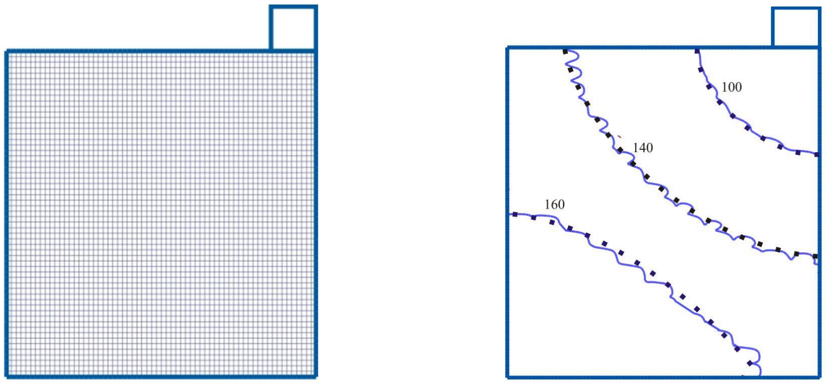


(a) Grid used by Yamada [14]

(b) Comparison between the results of the current simulation

Figure 1: Verification Sample

where ρc_p and λ are the thermal properties of each electrode, respectively [13]. The source term, q_i, is the heat generation source term which is also a function of temperature [14].

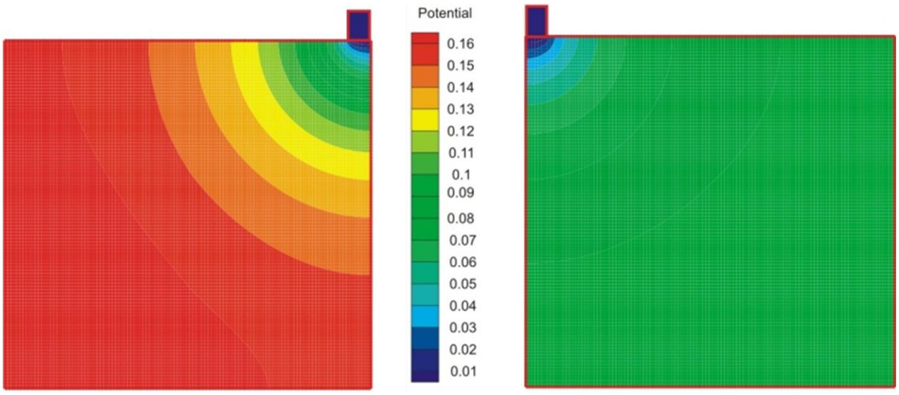
The current density doubles for each 10°C rise in the temperature or each 10% water loss, and on this basis the current density equation can be written as:

$$J_{\text{pos}} = J_{0.25} \times 2^{\left(\frac{T-25}{10}+\frac{f_{wl}}{0.1}\right)} \tag{3}$$

where, $J_{0.25}$ is the average charge transferred per unit volume at 25°C with no water loss, and f_{wl} is the constant parameter to calculate thermal properties of materials. The current density equation in the negative electrode is given by:

$$J_{\text{neg}} = \frac{J_{0.25}}{\theta} \times 2^{\left(\frac{T-25}{10}+\frac{f_{wl}}{0.1}\right)} \tag{4}$$

where, θ is a small volume fraction for the region near the interface where current exists and infinity for other regions in the negative electrode where there is no reactions.



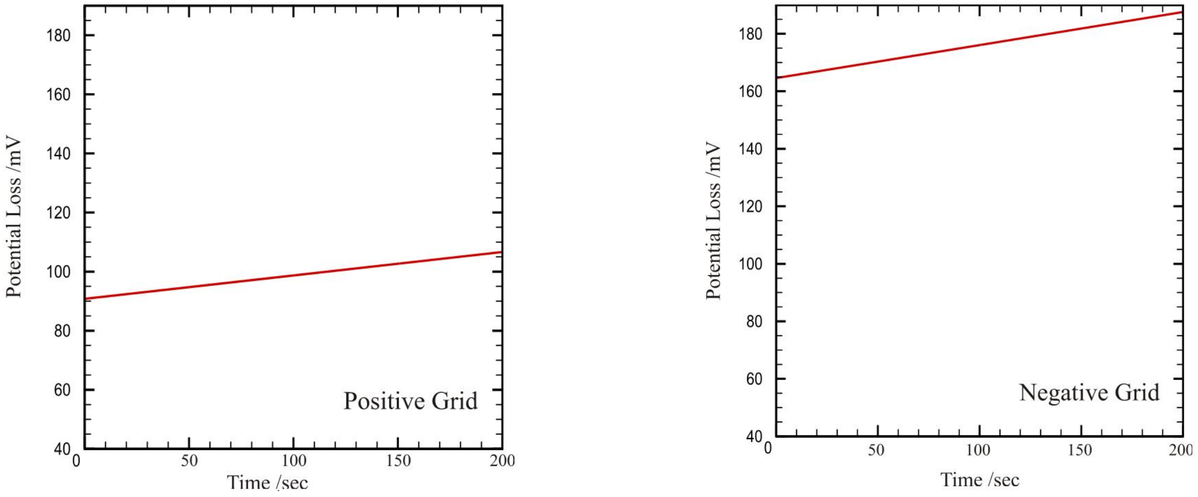
(a) positive grid

(b) negative grid

Figure 2: Isopotential lines for steady state mode

Beside the heat generation, the heat dissipation to the surrounding should also be taken into account. Dissipation of thermal energy is due to heat conduction in solid walls and convection to the ambient. For convenient, the heat dissipation can be calculated using resistant model. With the present model the heat dissipation can be written as:

$$q_{\text{dissip}} = R_{\text{dissip}}(T - T_a) = (R_{\text{conv}} + R_{\text{cond}})(T - T_a) = \left(\frac{1}{h_\infty} + \frac{d}{\lambda}\right)(T - T_a) \tag{5}$$



(a) Positive grid

(b) Negative grid

Figure 3: Variation of potential loss vs. time

In this equation, h_∞ is the convective heat transfer coefficient, d is the thickness of air gap between grid and battery case and λ is the heat conductivity. The equation of the corrosion thickness can be written as [15,16]:

$$\frac{\partial \delta}{\partial t} = -\frac{j_{\mathrm{corr}} \times M}{\rho F} \tag{6}$$

where δ is the corrosion thickness, M, ρ are the molar weight and density of the corroded grid, and F is the Faraday constant. Equations (1), (2) and (4) with the proper boundary conditions construct a system of governing equations which can be used to predict the potential drop, temperature distribution and corrosion of the positive and the negative plates. These coupled systems of nonlinear differential equations are discretized using the finite volume method.

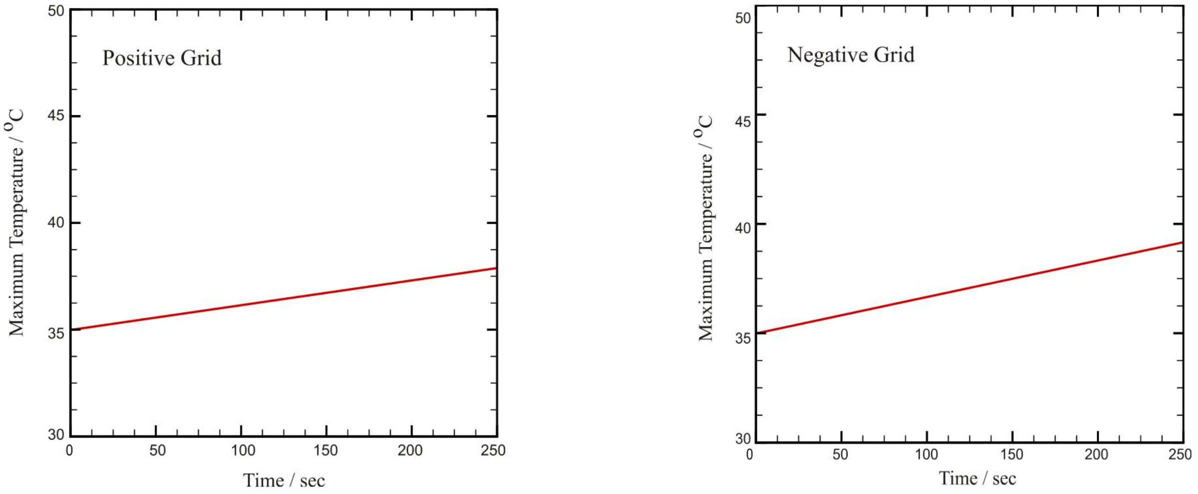
3 Results

The steady state and dynamic thermal behavior of a battery battery cell with 2.326 V are studied using the present model. The applied current for this study is taken to be 100 A which is a proper value for high discharge mode. In order to validate the results of the present study, they have been compared with the results presented by Yamada et al. [14] with the same grid dimension (Fig. 1(a)). The comparison is shown in Fig. 1(b). The total potential drop in this case was reported to be equal to 171.4 mV which agrees with the prediction of the current simulation with relative errors of 2% percent.

The isopotential lines for the positive and the negative electrodes for steady state mode are shown in Fig. 2. According to the figure, the potential drop near to lug, in both positive and negative grids, is high. On the other hand, potential drop in the positive grid is 165.8 mV and in the negative one is 110.4 mV. This difference makes sense because of the lower resistance of the negative plate.

Transient voltage drop is shown in figures 3(a) and 3(b). As it can be seen the voltage drop in the positive and the negative electrodes increases with respect to time. This happens because the internal resistance of the electrodes increases with discharge process.

The temperature graph of the positive and the negative grid is shown in the figures 4(a) and 4(b), respectively. According to the results the difference of temperature between the beginning and the end of discharge in the positive grid is 3.27°C, and in the negative grid is 2.12°C. The profiles show that because the heat generation rates at the positive electrode is relatively higher than the negative electrode, the change of the temperature at the positive electrode is slightly higher than the nearby negative electrode. Results show that if a battery operates in the ambient temperature at 35°C, the corrosion current density is 2 $\mu\mathrm{Acm}^{-2}$ and the corresponding corrosion thickness is 0.03 mm year^{-}1.



(a) Positive grid (b) Negative grid

Figure 4: Variation of Temperature vs. time

4 Conclusions

The present model is a two-dimensional, time dependent which can predict the potential drop, temperature on the grid in addition to the corrosion rate of the positive and the negative grids. The governing equations are fully coupled and solved iteratively. The value of potential drop during the discharge cycle is critical for lead-acid batteries which can be achieved with this model. Moreover, transient behavior of temperature has been studied in the positive and the negative electrodes which is a function of the non-uniform potential loss. Using the amount of the potential loss and temperature, the rate of corrosion has been calculated which is useful for realistic prediction of the lead-acid batteries. Hence this method can be employed in battery industry for many applications.

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