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Transient Thermal Characteristics Modeling and Simulation of Electrical Vehicle Battery Systems

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Abstract: Transient thermal characteristics modeling and simulation of electrical vehicle battery systems was carried out. A transient thermal model of battery systems was constructed. The electric and thermal characteristics of a single cell charge and discharge at 1C was simulated first. And then the temperature characteristics of battery systems under the WLTC (world light-vehicle test cycle) condition was studied. Results show that the model could reflect the temperature of cells in case of the SOC (state of charge) varies.

1. Introduction

The petroleum energy is the most important kind of energy used in the field of transportation. While the world is facing an petroleum energy crisis. Li-ion batteries have the characteristics such as high power densities and they have been widely used in the field of electric vehicles. And some of the railway vehicles have used the Li-ion battery pack as the power source [1, 2].

Li-ion battery cells could only work in a limited temperature range, which is usually -20℃~55℃. Otherwise, li-ion cell thermal runaway may occur, which is dangerous to passengers [3]. In the field of transportation application, the current of li-ion cells varies frequently which cause the transient temperature change. For thermal management engineers, it is the first step to know the thermal characteristics of the li-ion cell systems before the design of the thermal management systems of battery packs [4].

Experimental analysis of lithium-ion battery was done by researchers [5]. The electrical and thermal characteristics were studied at constant charge and discharge rates. The charge and discharge equipment, voltmeter, current probe, thermocouples, IR camera, power supply equipment were used.

Although experimental study could explore the lithium-ion cells characteristics, the growing need for fast prediction of lithium-ion cells for powertrain electrification demands fast modeling methods [6-9].

In this paper, the transient thermal model of electrical vehicle battery systems was conducted. And then the transient temperature of the battery systems was computed considering the cell SOC (State of charge) under the WLTC (world light-weight test cycle) condition.

2. Thermal Modeling of cells

The energy governing equations describing the temperature of the cell are given as follows [10]:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\frac{k\partial T}{\partial x_t}\right) + Q_{conv} + Q_{cond} + Q_{cell} \, (\mathrm{i} = 1, 2, 3) \tag{1}$$

$$Q_{conv} = h\left(T_{air} - T_{cell}\right) \tag{2}$$

$$Q_{cond} = \lambda\left(T_{plate} - T_{cell}\right) \tag{3}$$

Where ρ is cell density; k is heat conductivity of the cell; T is cell temperature; Q_{conv}, Q_{cond} and Q_{cell} are the convective heat transfer power, conductive heat transfer power and cell heat generating power, respectively; I, R and OCV are the current, resistance and the open circuit voltage of the cell;

h is convective heat transfer coefficient; λ is conduction coefficient. The index 1, 2, 3 indicates the three direction of the Cartesian coordinates.

The cell is simplified to a mass point. The Bernardi equation is used to compute the generated heat power of the cell [11]:

$$Q_{cell} = I^2 R + IT \frac{\partial OCV}{\partial T} \tag{4}$$

Although the Bernardi equation is relatively simple, it is physical and efficiency enough to compute the cell heat generation rate for a vehicle battery pack which usually concludes thousands of cells.

The OCV(open circuit voltage), charge resistance and discharge resistance is functions of SOC(state of charge) and temperature of the lithium-ion cell. Figure 1 presents the OCV of a commercial 47.5Ah lithium-ion cell simulated in this paper.

As can be seen in Figure 1, the OCV decreases as the SOC decreases, and the OCV decreases as the temperature increases.

Figure 2 presents the DCR of the lithium-ion cell simulated in this paper.

As can be seen in Figure 2, both the charge and discharge DCR decreases as the cell temperature increases. While there is a nonlinear relation between DCR and the SOC of the cell.

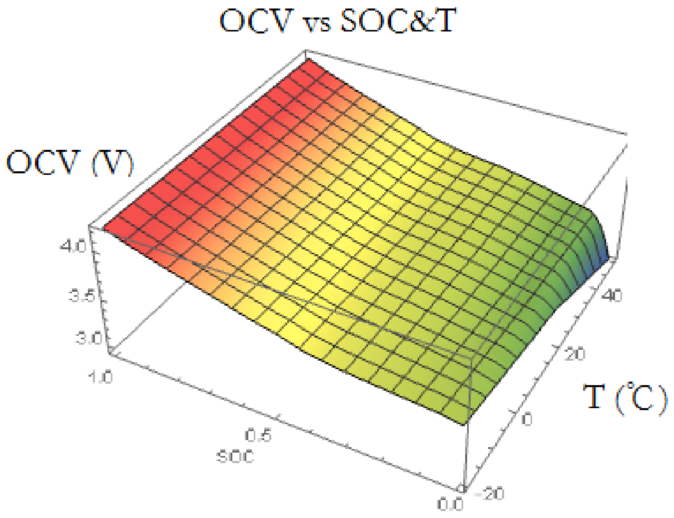
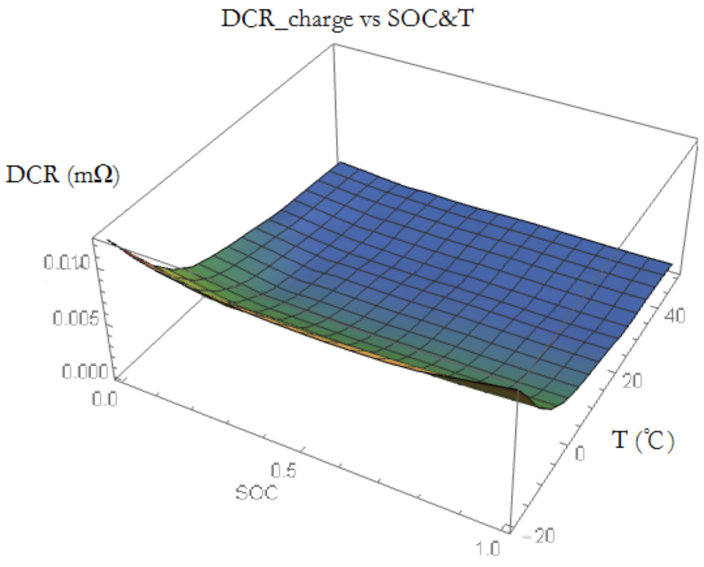
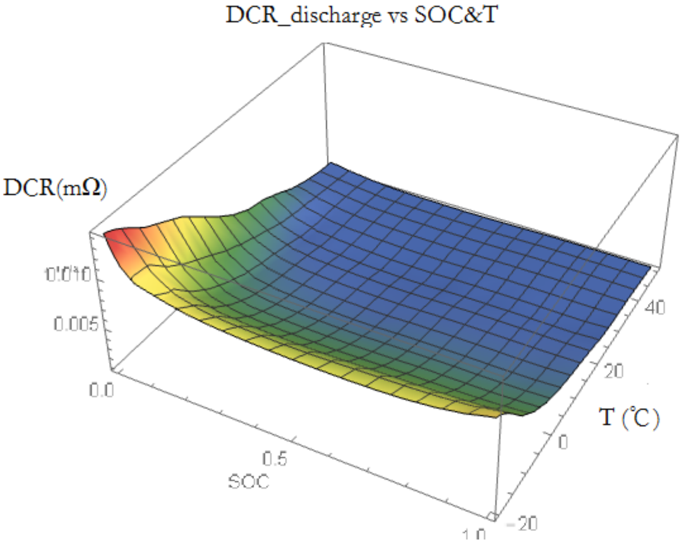


Figure 1. The OCV (open circuit voltage) of the cell with the SOC and temperature of the cell



(a)



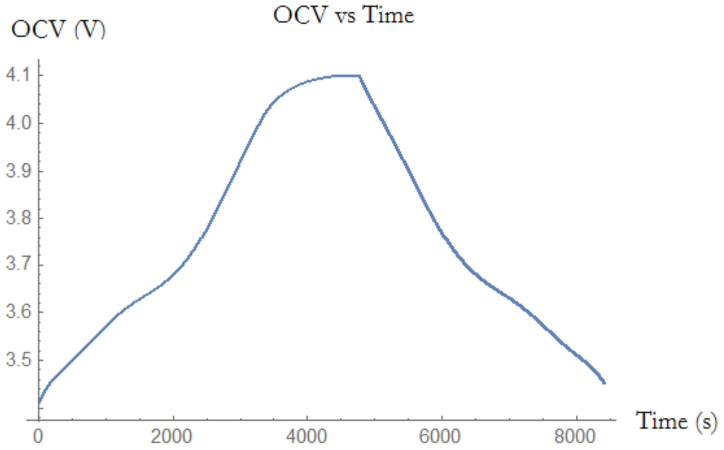
(b)

Figure 2. The DCR (direct current resistance) of the cell with the SOC and temperature of the cell (a) charge DCR, (b) discharge DCR

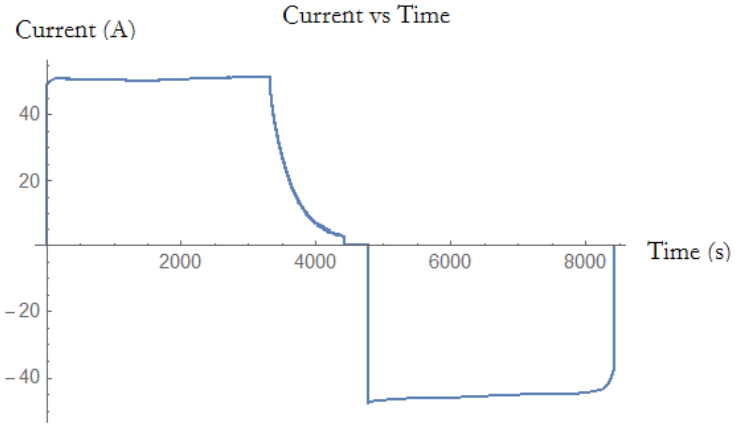
3. Model and computation process verification

The 1C charge and discharge process of a single cell is studied first. And the computational results of cell temperature at the 1C charge and discharge are compared with experiment data of cell temperature to verify the model and computational process.

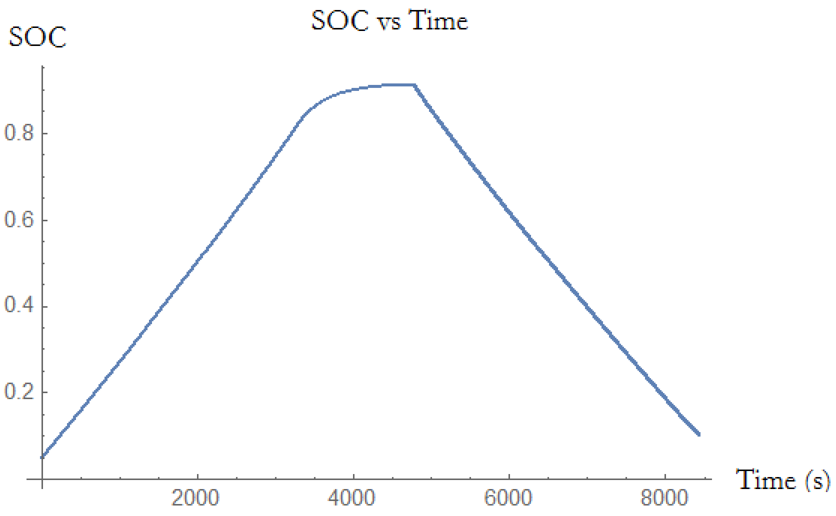
Figure 3 presents the OCV, current, SOC, heat power generation and the temperature of the cell.



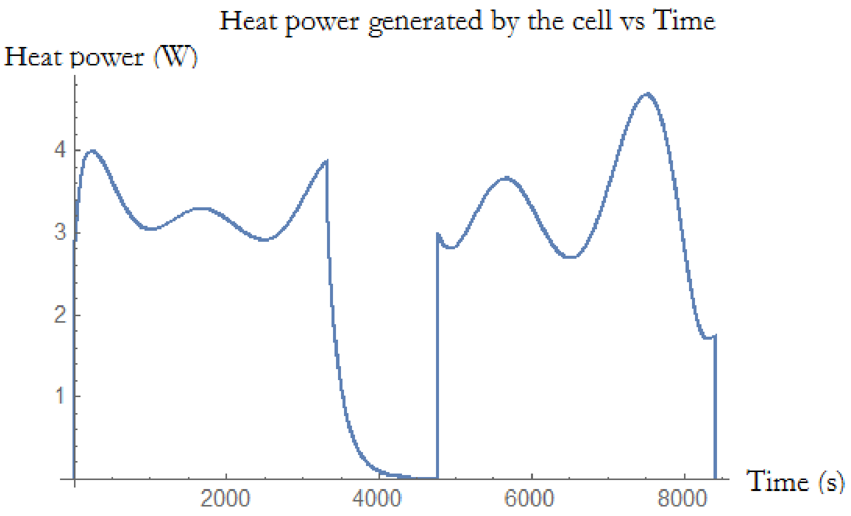
(a) OCV



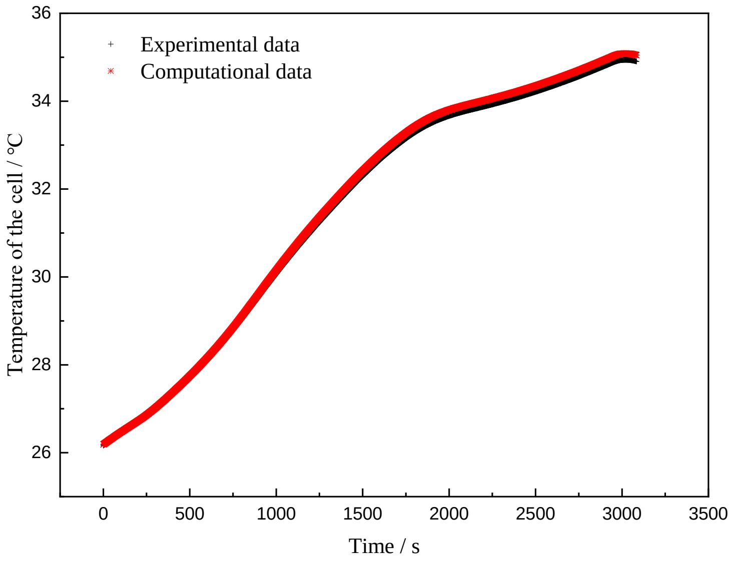
(b) current


SOC vs Time

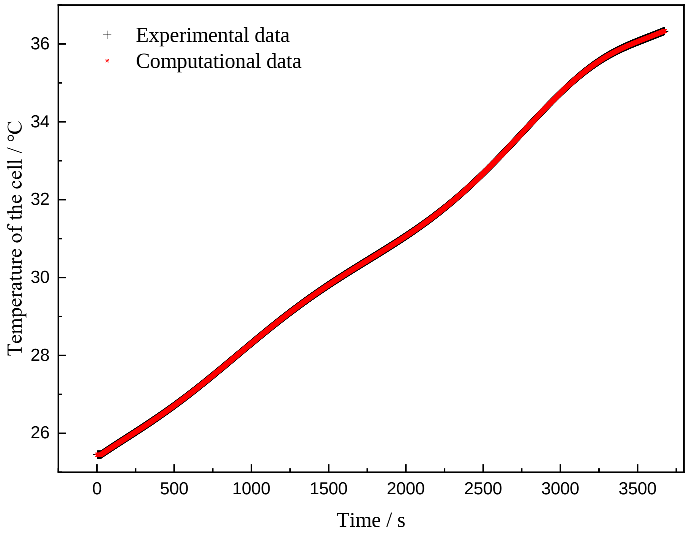
(c) SOC


Heat power generated by the cell vs Time

(d) heat power



(e) cell temperature at 1C charge



(f) cell temperature 1C discharge

Figure 3. The charge and discharge characteristics of a 47.5Ah cell (a) OCV, (b) current, (c) SOC, (d) heat power, (e) 1C charge cell temperature, (f) 1C discharge cell temperature

As can be seen in Figure 3(a) and Figure 3(b), the 47.5Ah cell charge at 1C first, and then discharge at 1C. As can be seen in Fig. 3(a), the open circuit voltage increases almost linearly at the start of the charge process, and then the trend of the voltage increasing slows as the charge processes. In the discharge process, the voltage decreases dramatically first, and then the trend of the voltage decreasing slows.

As can be seen in Fig. 3(c), the SOC increases linearly and then trend of the increasing slows as the cell charges. When the cell discharges the SOC decreases linearly.

As can be seen in Fig. 3(d), the heat power generated by the cell in a nonlinear style, because the resistance of the cell changes with SOC and temperature.

As can be seen in Fig. 3(e) and Fig. 3(f), the computational data are in accord with the experimental data of the cell temperature.

4. Temperature of cells under WLTC working condition

The WLTC is a typical working condition for vehicles [12]. The WLTC defines the velocity of the vehicles, which is corresponding to the power of the motor of the electrical vehicle. First, the corresponding current of the cell is computed. Figure 4 presents the current of the cell under the WLTC condition.

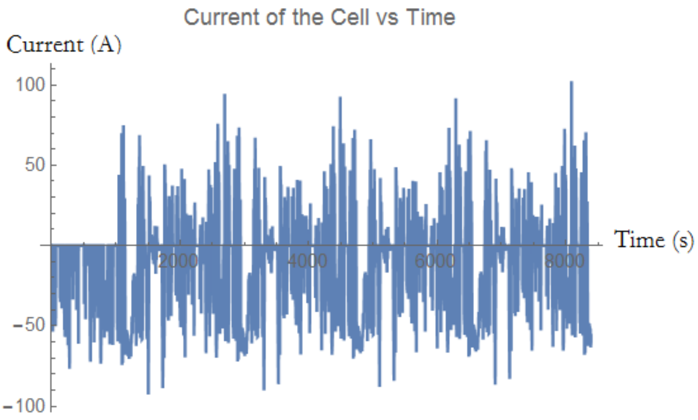


Figure 4. The transient current of the cell under the WLTC condition

Figure 5 presents the OCV of the cell under the WLTC condition.

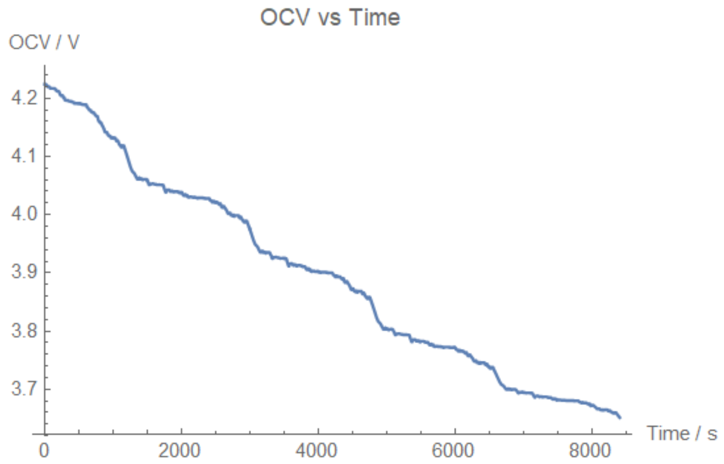


Figure 5. The transient OCV of the cell under the WLTC condition

Figure 6 presents the SOC of the cell under the WLTC condition.

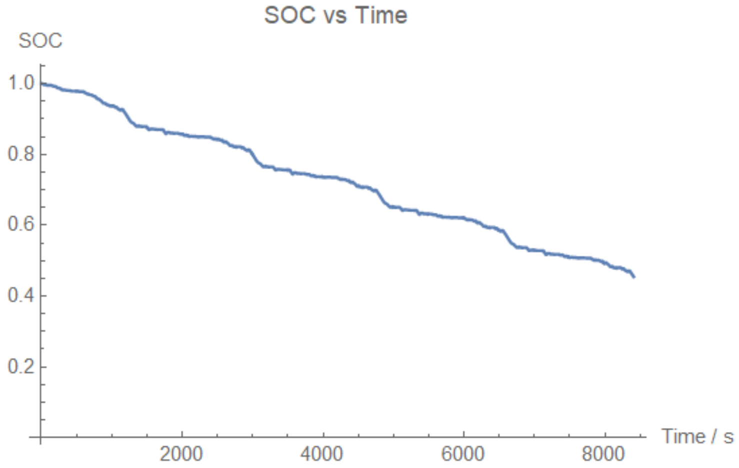


Figure 6. The transient SOC of the cell under the WLTC condition

The heat generating power of the cell is computed using the Eq. (4). Figure 7 presents the transient heat power generated by the cell under the WLTC condition.

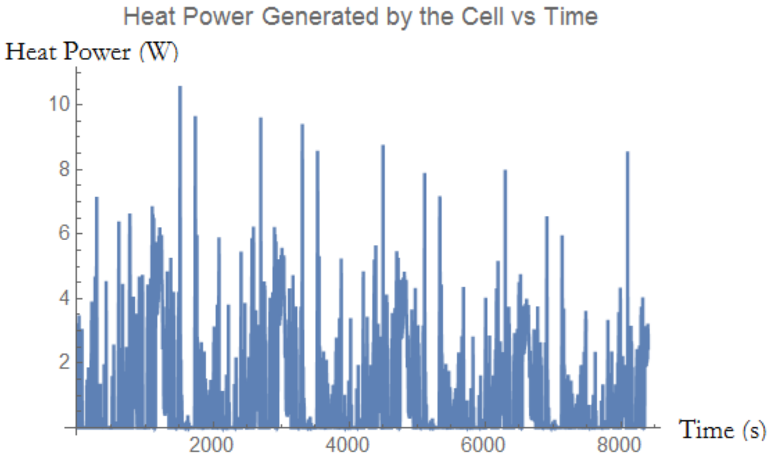


Figure 7. The transient heat power generated by the cell under the WLTC condition

Finally, the transient temperature of the cell under the WLTC condition is computed. The conductive and convective heat transfer for the cells could be computed using equations (2) and (3). Figure 8 presents the temperature of cells working under the WLTC condition.

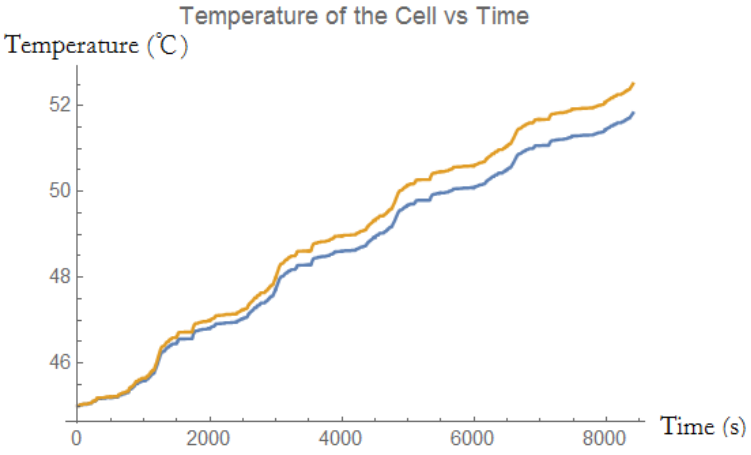


Figure 8. The transient temperature of the battery system under the WLTC condition (yellow line: highest temperature of the cell in a battery pack; blue line: lowest temperature of the cell in a battery pack)

Usually, there are hundreds even thousands of cells in a battery pack system. The convective and conductive heat transfer condition is different from cell to cell. As can be seen in Fig. 8, there is a temperature difference for cells in a battery pack.

5. Conclusions

This paper presents a theoretical model to predict the transient temperature of cells in a battery pack of an electrical vehicle. In the theoretical model, the charge resistance, the discharge resistance and the open circuit voltage are considered which are functions of SOC and temperature of cells. The temperature of the cells working under the WLTC cycle is simulated. The charge resistance, the discharge resistance, the open circuit voltage are all functions of the aging rate of the lithium-ion cells. With the change of these parameters, the aging rate of the lithium-ion cells could be considered in the temperature results.

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