Theoretical and numerical validation for thermal modeling of EV battery cell

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Abstract. Battery packs are extensively used in electrical vehicles (EV) to avoid environmental pollution. The safety, aging and life of battery cell are significantly related to its thermal behavior. This work concerns with thermal analysis and measurement of an EV battery cell of 153Ah. The Bernardi’s heat generation model is employed and the reversible heat is taken into account. The reversible heat is related to the entropy coefficient and it is tested and presented as a relation to SOC. The specific heat capacity and the relationship between the heat and the temperature rise of battery cells are tested by the EV-ARC. The heat generation model is validated by tests at 0.2 C, 0.67 C and 1.2 C discharging rates. It reveals that the reversible heat is not negligible especially at low rate discharge. Then the heat generation model is applied to a cell model to verify the temperature of the cell. The numerical results from this thermal modeling of the battery cell are in good agreement with the test results.

1. Introduction

Battery pack is one of the most important components of electrical vehicles (EVs), the performance of the battery pack is mainly affected by the performance of the battery cell, when batteries are working in the condition of high or low temperature or battery cells are present with unbalanced temperature, it will lead to accelerated battery aging, decreased discharging performance and even worse, serious battery safety accidents, e.g., thermal runaway and propagation. Therefore, thermal management analysis is crucial for studying thermal behavior of battery cell.

In thermal analysis of battery cells, the generated heat from battery cells is an important source of heat. So far, there are two means to obtain this physical parameter. The first one is based on thermal-electro-chemical battery model, which enables our attention to be paid on the underlying mechanism of heat generation; however, this model requires a large number of electro-chemical parameters and these unknowns are difficult to determine. The second one is the simplified Bernardi’s heat generation model [1] which is wildly used because of physical-based property and few parameters are required. In the Bernardi’s heat generation model, the entropy coefficient is an important parameter as it is related to reversible heat. This important parameter, however, is difficult to test and determine and sometimes neglected or assumed to be a constant. Apparently, these simplified treatments will lead to the bias of the generated heat between the calculation and the test, and thus it is necessary to measure and calculate the real values of the entropy coefficient. To obtain this parameter, small-capacity cells of 18650 were selected by Al Hallaj et al [2], and medium-size capacity cells were selected by Zhang et al. [3], but unfortunately, large-capacity cells are rarely used to conduct research as from literature. Considering a
large-capacity cell has less heat releasing rate due to the small ratio of surface to volume, we use a large-capacity cell of 153 Ah to investigate the entropy coefficient for thermal management analysis of a battery pack in this research.

In this research, the accurate heat generation model of a single cell is formulated and validated by tests with the consideration of reversible heat. Specifically, the internal resistance and open circuit voltage (OCV) of cells are acquired under the condition of varying temperature and state of charge (SOC) by tests. To obtain the heat generation of cells, the irreversible heat, which is based on the internal resistance, and the reversible heat, which is related to the entropy coefficient, are calculated by means of the Bernardi’s model [1]. It should be noted that the entropy coefficient is obtained based on the test data from a Ni-Co-Mn lithium-ion battery with the capacity up to as large as 153 Ah. The heat generation and temperature of the battery cell are tested by the extended volume-accelerating rate calorimetry (EV-ARC) at different discharging rates, and it would find that the tested heat generation agrees well with that obtained by the Bernadi’s model and the tested temperature is in good agreement with the simulation results.

2. Heat generation model of battery cells

The Bernardi’s heat generation model is formulated at first, and then the EV-ARC test results and numerical results are employed to validate the heat generation model.

2.1. Formulation of the heat generation model.

To analyze the thermal behaviour of the battery pack, the heat generation model of battery cells is critical. Generally, there are two categories of heat generation models. The first one is based on thermo-electrochemical battery model and studies the mechanism of heat generation. However, this model requires a large number of electrochemical parameters of battery, and moreover, these parameters are hard to determine. The second one is the widely-used Bernardi’s heat generation model [1] and only few parameters are required. For simplicity, the latter one is employed in this research.

According to the Bernardi’s heat generation model [1], its simplified form can be given as

\[ Q = I^2R + IT\frac{dU_{oc}}{dT} \]  

(1)

where \( Q \) is the total heat generation rate from the battery cells; \( I \) is the working current of the battery (\( I \) is positive when charging and negative when discharging); \( R \) represents the equivalent internal resistance of the circuit, and is usually calibrated by the current-off method [4]; \( U_{oc} \) is the open voltage of the battery circuit; \( V \) is the working voltage of the battery; \( T \) is the temperature of the battery and \( dU_{oc}/dT \) means entropy coefficient which in general describes the entropy change of the battery cells.

The first term on the right hand side of Eq. 1 is Joule heating. It is in fact the irreversible heat generation rate \( Q_{ir} \) and caused by battery internal resistance. The second term on the right hand side of Eq. 1 implies reversible heat generation rate \( Q_r \), which represents the charging and discharging characteristics of cells.

To determine the reversible heat generation rate \( Q_r \), the entropy coefficient \( dU_{oc}/dT \) has to be known; however, this unknown variable cannot be directly obtained from the test. The potentiometric method and the calorimetric method are often applied for its measurement [3]. Two steps need to be carried out to obtain the entropy coefficient. Firstly, the relationship between the OCV and the SOC of battery cells at different temperature is obtained by the offline OCV tests [5]. Secondly, the OCV measurement data at each SOC are fit and normally found to be approximately linear to the temperature, thus the slope, i.e., the \( dU_{oc}/dT \), can be derived. A correlation of the entropy coefficient \( dU_{oc}/dT \) to the SOC is then obtained by the test and plotted as shown in Figure 1. Note that this curve of entropy coefficient will be applied to the heat generation model of cells in Section 3.
Figure 1. Correlation of entropy coefficient to SOC

The OCV measurements require long relaxation time, which requires from a few minutes to even hours, and the accuracy depends on hysteresis phenomenon and recovery effect; therefore, the entropy coefficient is hard to obtain and usually neglected or assumed to be a constant instead, leading to a zero or inaccurate reversible heat generation rate $Q_r$. Details of the impact from these simplified treatments are discussed in Section 2.3

2.2. EV-ARC tests of battery’s heat generation

EV-ARC is employed to test the specific heat capacity ($C_p$) and the heat generation ($W$) of battery cells. To test $C_p$, two cells is sandwiched by a heating pad (shown in Figure. 2(a)) which is provided with a constant external heating power $P$. Then, according to the energy conservation that the heat input to the cells transforms to the temperature rise ($\Delta T$) of the cells, that is

$$P\Delta t = C_p m_s \Delta T$$

(2)

Where $\Delta t$ is the heating time and $m_s$ the mass of the sandwich structure. Rearranging Eq. 2, yields

$$C_p = \frac{P}{m_s} \cdot \frac{1}{\Delta T/\Delta t}$$

(3)

As the temperature rise $\Delta T$ and the heating time $\Delta t$ can be directly obtained by the EV-ARC test, the specific heat capacity $C_p$ can then be calculated by Eq. 3. Once the $C_p$ is known, a cell with different discharging rates (1.2 C, 0.67 C and 0.2 C) is tested by the EV-ARC (as shown in Figure. 2(b)) to obtain the relation between the heat generation $W$ and the temperature rise $\Delta T$, i.e.,

$$W = C_p m_c \Delta T$$

(4)

In which, $m_c$ indicates the mass of the cell; the heat generation $W$ of the tested cell is contributed by both the irreversible heat generation rate $Q_{ir}$ and the reversible heat generation rate $Q_r$. It should be noted from Figure. 2(b) that the temperature is monitored by a negative temperature coefficient (NTC) sensor which is paced in the middle of the cell’s large face.
2.3. Theoretical validation of the heat generation model
The results of heat generation against the depth of discharge (DOD) at different discharging rates (1.2 C, 0.67 C and 0.2 C) are obtained by the EV-ARC tests and plotted as shown in Figure 3. The theoretical results from the Bernardi’s model with or without considering reversible heat are compared in plots as well. From the Figure, it can be found that the results of the heat generation agree much better with the test results at three different discharging rates when the reversible heat generation rate $Q_r$ is taken into account. Moreover, the agreement between the test results and the theoretical results without considering $Q_r$ gets worse with the decreasing discharging rate. It should be noted that from the figure, the increase of heat generation results become slower between the 40% and 70% DOD. This is because the entropy coefficient is positive (as shown in Figure 1) when the SOC ($SOC = 1 - DOD$) ranges from 30% to 60%. In a discharging condition, the working current $I$ is negative and so that the reversible heat $Q_r$ contributes negatively to the total generated heat. In a particular case of discharging rate being 0.2 C, the negative contribution of $Q_r$ is greater than the irreversible heat $Q_{irr}$, thus $Q$ drops in a certain range where the entropy coefficient is positive, So the $Q_r$ plays a more significant role than the $Q_{irr}$ in the case of small discharging rate.

From the above discussion, it is summarized here that the heat generation model is accurate and the reversible heat cannot be neglected especially for cases with small discharging rates.

3. Numerical validation of the heat generation model
Battery cells are used for numerical validation and the heat generation model formulated in Section 2.1 is employed with taking account of the reversible heat. Physical and thermal properties of cells are shown in Table 1. Cells are discharging in an adiabatic boundary condition at different discharging rates with the SOC changing from 100% to 0. NTC sensors are placed in the center of cells’ large surface to record the temperature variation.
Table 1. Technical parameters for a 153 Ah Lithium-ion battery

| Parameters                        | Values          |
|-----------------------------------|-----------------|
| Rated capacity                    | 153.0 Ah        |
| Rated voltage                     | 3.7 V           |
| Internal resistance               | ≤0.8 mΩ         |
| Specific heat capacity            | 1000.0 J/kg/K   |
| Density                           | 2277.0 kg/m³    |
| Size of cell (length \times width \times height) | 79×148×95 mm   |
| Thermal conductivity (X direction) | \( k_x \) 2 W/m/K |
| Thermal conductivity(Y direction) | \( k_y \) 20 W/m/K |
| Thermal conductivity (Z direction)| \( k_z \) 15 W/m/K |

As from the temperature distribution in Figure 4, the maximum temperature decreases with less discharging rate, which is in agreement with the interpretation of the heat generation model. As for each figure, the maximum temperature appears in the positive electrode because it is made of aluminum and the resistance is larger compared to the other components of cells. By looking into the temperature variation of the center of the large surface, it can be found that the numerical results agree well with the test results by the NTC sensor at three different rates as shown in Figure 5. The errors between the numerical and test results are within 5%. As the DOD increases from 40% to 70%, the trend of both the numerical and test results get slower, which is in good agreement with the theoretical validation, and the reason to this change is also the entropy coefficient being positive in this range.

![Figure 4](image)

**Figure 4.** Temperature distribution of the cell at different discharging rates: (a) 1.2 C, (b) 0.67 C and (C) 0.2 C

![Figure 5](image)

**Figure 5.** Comparison between simulation and test results at different discharging rates

4. Conclusion
The Bernardi’s heat generation model is employed and the reversible heat is taken into account. The reversible heat is related to the entropy coefficient and it is tested and presented as a relation to SOC.
The specific heat capacity and the relationship between the heat and the temperature rise of battery cells are tested by the EV-ARC for thermal analysis of battery packs. The heat generation model is validated by tests at 0.2 C, 0.67 C and 1.2 C discharging rates, and it is found that the theoretical results with the reversible heat taken into account match better with the test results than the one without the consideration of reversible heat. In addition, results from this comparison also reveal that the irreversible heat is sensitive to large discharging rate whereas the reversible heat plays an important role in the case of small discharging rate. Numerical results from a battery cell also validate the heat generation model at three different discharging rates and confirm the importance of the reversible heat. The errors between the numerical and test results from this thermal modeling of the battery cell are within 5%. The proposed battery cell model can be applied to EV battery packs in the future work.

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