Thermal modeling and validation for EV battery packs in realistic operation conditions

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Abstract. Battery pack is one of the most important components of electrical vehicles (EV). The safety, aging and life of battery packs are significantly related to its thermal behavior. This work concerns with thermal behavior of an EV battery pack for realistic engineering applications. The Bernardi’s heat generation model with the consideration of reversible heat is employed and validated by tests and numerical simulation on battery cells. Then the validated cell model is applied to an EV battery pack with cooling system underneath for the study of thermal behavior in a realistic operation condition, and numerical results are in good agreement with the test results.

1. Introduction
The battery pack, as one of the most important components of electrical vehicles (EVs), is sensitive to operating temperature on its performance. To be specific, 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 issues, e.g., thermal runaway and propagation, fire or explosion. Therefore, thermal management analysis is crucial for studying thermal behavior of battery packs.

In thermal analysis of battery packs, the generated heat from battery cells is an important source of heat. The simplified Bernardi’s heat generation model [1] 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, so that sometimes it has to be neglected or assumed 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.

A great number of researches have been focused on the thermal behavior of a single cell [2,3]; however, single cell neither reflects the temperature-rising property of module and pack, nor takes account for the heat dissipation effect of cooling system which is crucial to the battery pack. Smith et al. [4] hence put emphasis on a battery module with the capacity of 25 Ah and studied the influence of inlet temperature and flow flux to the battery temperature; however, the temperature difference between battery modules, which is important to battery pack, cannot be obtained. Chen et al. [5] made a preliminary study at a battery pack level with focus on the effect of radiation heat transfer to battery pack.

In this research, a real EV battery pack with cooling system underneath from the GAC Motor is employed as our model for thermal analysis in a realistic operation condition. Firstly, the accurate heat
generation model of a single cell is formulated and validated by tests with the reversible heat taken into account. 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. Then, on the basis of the validated cell models, a commercial EV battery pack with cooling system underneath is established for 3D thermal analysis in a realistic operation condition.

2. Heat generation model of battery cells

2.1. Formulation of the heat generation model

The heat generation model of battery cells is critical to analyze the thermal behaviour of battery packs. The widely-used Bernardi’s heat generation model [1] is employed in this research.

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

\[ Q = I(U_{oc} - V) + T \frac{dU_{oc}}{dT} \]  

where \( Q \) is the total heat generation rate from the battery cells; \( I \) is the working current of the battery (positive when charging and negative when discharging); \( R \) represents the equivalent internal resistance of the circuit; \( U_{oc} \) is the open voltage of the battery circuit; \( V \) is the working voltage of the battery; \( T \) is the temperature of the battery and \( \frac{dU_{oc}}{dT} \) 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 \( Q_i \) 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 \( \frac{dU_{oc}}{dT} \) 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 [6]. A correlation of the entropy coefficient \( \frac{dU_{oc}}{dT} \) to the SOC (state of charge) is obtained by the test and plotted as shown in Figure 1.

![Figure 1. Correlation of entropy coefficient to SOC.](image)

2.2. 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/m$^3$      |
| Size of cell (length × width × 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       |

The temperature distribution is shown in Fig. 2 and 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 as shown in Fig. 3. The errors between the numerical and test results are within 5%. As the DOD (depth of discharge) 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 the entropy coefficient being positive in this range.

![Figure 2. Temperature distribution of the cell.](image)

![Figure 3. Comparison between simulation and test results.](image)
3. Thermal analysis for EV battery packs

3.1. Model description of the EV battery pack

The 3D model of the EV battery pack with cooling system underneath is shown in Fig. 4, where the thermal conductive pad is inserted in-between them. The inlet and outlet are sketched in the figure as well, and the outlet is with the pressure of 1 atm. The computational model consists of 21 million elements. Thermal physical properties of lithium-ion battery are shown in Table 2. Heat conduction between neighboring cells, and between cells and thermal conductive pad is taken into account. Moreover, convective heat between cells and environment, and between coolant and thermal conductive pad is also under consideration. The heat transfer via radiation is relatively small in battery thermal modeling and is thus neglected.

| Material                | Density (kg/m³) | Thermal conductivity (W/m/K) | Specific heat (J/kg/K) | Dynamic viscosity (Pa/s) |
|-------------------------|-----------------|------------------------------|------------------------|--------------------------|
| Al                      | 2710.0          | 155.0                        | 890.0                  | /                        |
| Cu                      | 8940.0          | 398.0                        | 386.0                  | /                        |
| Thermal conductive pad  | 2400.0          | 2                             | 2200.0                 | /                        |
| Coolant                 | 1069.4          | 0.4                           | 3358.0                 | 0.0034                   |

In a realistic operation condition of cooling condition, which normally is a case when EVs are driving uphill of 3% slope with a constant speed of 120 km/h for 35 minutes in the summer, the heat source is the battery cells whose initial temperature is much higher than the coolant and is working with a high discharging rate. The heat generation model as stated above is applied to describe the amount of heat generated, and note that the obtained heating power from the EV battery pack in cooling condition is shown in Fig. 5. Some boundary conditions are given as follows. The inlet temperature is 25 °C, the inlet flow 10 L/min, the initial temperature of battery 37 °C and the environmental temperature 40 °C.

![Figure 4. 3D model of battery pack with cooling system underneath.](image)

![Figure 5. The heating power of the EV battery pack in cooling condition.](image)
3.2. Validation in cooling condition

The summary of simulation and test results are compared in Table 3. It can be seen that when the battery pack is working in cooling condition for 35 minutes, the maximum temperature differences $\Delta T_{\text{max}}$ for simulation and test results are 3.9 ℃ and 4.0 ℃, respectively. The results from both numerical simulation and test are in excellent agreement. The maximum temperature rise from numerical result that of 12.5 ℃ also agrees very well with the test result that of 12.0 ℃. The temperature histories for both simulation and test results are shown in Fig. 6, where simulation results for both the maximum and minimum match test results in the entire cooling period. It needs to mention that the initial temperature of the test results is moved from 33.0 ℃ to 37.0 ℃ for a better comparison.

![Figure 6. Comparison between numerical and test results in cooling condition.](image)

| Summary of simulation and test results in cooling condition. |
|-------------------------------------------------------------|
| Initial temperature (°C) | Final temperature (°C) | Max Temp rise (°C) |
|--------------------------|-------------------------|--------------------|
| $T_{\text{max}}$ | $T_{\text{min}}$ | $\Delta T_{\text{max}}$ | $T_{\text{max}}$ | $T_{\text{min}}$ | $\Delta T_{\text{max}}$ |
| Simulation | 37.0 | 37.0 | 0 | 49.5 | 45.6 | 3.9 | 12.5 |
| Test | 37.0 | 33.0 | 4.0 | 49.0 | 41.0 | 4.0°(8.0) | 12.0 |

*Notes: 4.0 is the real temperature difference considering the initial temperature gap is 4.0.

![Figure 7. Temperature distribution of battery pack in cooling condition.](image)
4. Conclusion
Thermal analysis for a battery cell (153Ah) is conducted at a discharging rate of 0.2 C. The Bernardi’s heat generation model is employed and the reversible heat is taken into account. Numerical results from a battery cell validate the heat generation model at 0.2 C discharging rate and confirm the importance of the reversible heat. The heat generation model of cells is applied to an EV battery pack for thermal modeling in a realistic operation condition. Numerical results show that the maximum temperature difference $\Delta T_{\text{max}}$ and the maximum temperature for simulation results match well with the test results. In addition, it can be found that the temperature histories for both simulation and test results are in good agreement in the entire cooling period. The validated thermal model can be further applied to study thermal behavior of other EV battery packs.

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