

Design and Thermal Analysis of a Passive Thermal Management System Using Composite Phase Change Material for Rectangular Power Batteries

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ABSTRACT

A passive thermal management system (TMS) using composite phase change material (PCM) for large-capacity, rectangular lithium-ion batteries is designed. A battery module consisting of six Li-ion cells connected in series was investigated as a basic unit. The passive TMS for the module has three configurations according to the contact area between cells and the composite PCM, i.e., surrounding, front-contacted and side-contacted schemes. Firstly, heat generation rate of the battery cell was calculated using the Bernardi equation based on experimentally measured heat source terms (i.e. the internal resistance and the entropy coefficient). Physical and thermal properties such as density, phase change temperature, latent heat and thermal conductivity of the composite PCM were also obtained by experimental methods. Thereafter, thermal response of the battery modules with the three TMS configurations was simulated using 3D finite element analysis (FEA) modeling in ANSYS Fluent. Simulation results show that, when PCM is adequate, surrounding and front-contacted schemes are better than the side-contacted scheme in battery temperature control. While when PCM is not adequate under continuous 3C charge-discharge cycle, front-contacted and side-contacted schemes show a better performance in PCM utilization rate in the late period of melt process than the surrounding scheme due to a higher heat conduction rate from the cells to the PCMs. This paper is expected to provide useful guidelines for the design of the passive TMS in rectangular power battery applications.

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INTRODUCTION

In recent years, lithium-ion batteries have become the prime selection for power sources of hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs). These state-of-art batteries in mass production show good performance on energy capacity, cycle life, operating safety and self-discharge, etc. However, these properties are greatly affected by the cell operating temperature and differential cell temperature [1]. Low temperature will diminish both the energy and power capacities, resulting in a worse performance of HEVs and BEVs. On the other hand, high temperature can accelerate the decomposition rate of membranes and electrodes etc., and even lead to dangerous situations of catching fire or explosion. Moreover, temperature difference among cells and modules will cause uneven electrochemical reaction rates, which is inclined to cause a premature failure of the whole pack. Thus, it is vital to keep the power battery operating in its optimal temperature range and within a certain temperature difference from cell to cell and module to module [2].

A thermal management system (TMS) for power batteries can be classified as passive or active type according to whether there are built-in heat sources or not. Also, TMS can be classified as air cooling, liquid cooling, phase change material (PCM) cooling, heat pipe cooling and combination of these based on the heat transfer medium. The passive PCM cooling, in which PCM absorbs and

releases a large amount of latent heat during solid/liquid phase change cycles, has been proven to be an effective and feasible solution for power battery thermal management. A certain amount of experimental and numerical studies have been conducted on PCM cooling in the last decade. Khateeb et al. [3] designed a PCM cooling system for cylindrical lithium-ion batteries in electric scooter applications. Experimental results showed that the combination of aluminum foam (which was used for heat transfer enhancement of PCM) and PCM reduced the battery temperature rise by 50% and the battery thermal uniformity was also improved. Kizilel et al. [4] tested discharging performance of a battery pack with PCM cooling under extreme operating conditions (i.e. ambient temperature of 45°C and constant-current rate of 2.08C). Compared with the battery pack without TMS, capacity decay rate of the pack with PCM cooling system was reduced by 50%. Rao et al. [5] conducted both experiments and simulation on a PCM cooling system for rectangular lithium-ion batteries. They concluded that performance of the passive TMS can be enhanced by improving the thermal conductivity of batteries and properly reducing the phase change temperature of PCMs. To the authors' knowledge, PCM cooling for large-capacity and rectangular power batteries has not been adequately investigated. Especially, comparison of different configurations of PCM cooling has not been reported in previous literatures so far.

An effective TMS for a battery pack requires a good understanding of the heat generation behavior within the cells and good thermal design of the TMS [6]. This paper starts with the calculation of heat generation rate of the battery cell based on the Bernardi equation. Thereafter, three different PCM cooling schemes for a commercial and rectangular Li-ion battery (as shown in Figure 1) are proposed. The cooling performance of these three TMSs during constant-current discharge processes are then analyzed by the numerical simulation method in the commercial software ANSYS Fluent.

BATTERY HEAT GENERATION

Bernardi Equation

According to the Bernardi equation [7], the heat generation rate, q , of a lithium-ion cell can be calculated by

$$q = I^2 R_t - IT \frac{\partial E}{\partial T} \quad (1)$$

where I is the current, A; R_t is the total internal resistance, Ω ; T is the temperature in Kelvin; E is the open circuit cell voltage, V; $\partial E / \partial T$ is called the entropy coefficient, $V \cdot K^{-1}$. For the right side of Equation (1), the first part of $I^2 R_t$ is the irreversible heat caused by internal resistance and electrochemical polarization, and the second part is the reversible heat caused by enthalpy change during battery electrochemical reactions.

Considering that R_t and $\partial E / \partial T$ all vary with temperature and depth of discharge (DOD), Equation (1) can be developed into a more specified form as given in Eq. (2).

$$q(\text{DOD}) = I^2 R_t(\text{DOD}) - IT \frac{\partial E}{\partial T}(\text{DOD}) \quad (2)$$

With the experimentally obtained R_t and $\partial E / \partial T$ at different temperatures and DODs, the cell heat generation rate at any discharging time can be calculated by Equation (2). Measurement of internal resistance and entropy coefficient of the test battery, whose primary parameters are detailed in a previous work of our group [8], will be detailed in the following sections.

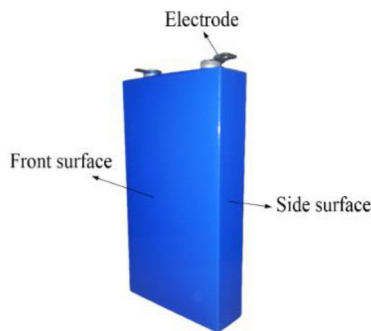


Figure 1. The battery cell.

Internal Resistance

There are several kinds of methods for battery internal resistance measurement such as the voltage-current characteristics method, the difference between OCV and the cell terminal voltage, the ac

impedance meter and the hybrid pulse power characterization (HPPC) method [9,10]. Cell internal resistance in this work was measured by the HPPC method. As shown in Figure 2, when a pulse current of 10 s (according to test procedures in Ref. [10]) is applied to a battery cell, the terminal voltage shows a step change, ΔU_o , promptly, which is caused by the ohmic internal resistance, R_o . After that, the terminal voltage diminishes gradually due to the polarization effect.

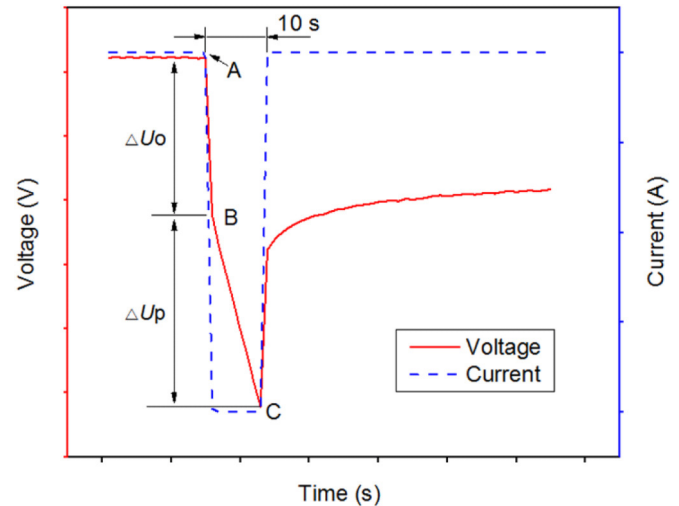


Figure 2. Current and voltage profiles during HPPC measurement.

R_o and polarization resistance, R_p , during discharge can be calculated by Eq. (3) and Eq. (3), respectively.

$$R_o = \frac{\Delta U_o}{I} = \frac{U_B - U_A}{I} \quad (3)$$

$$R_p = \frac{\Delta U_p}{I} = \frac{U_C - U_B}{I} \quad (4)$$

where U_A , U_B and U_C are the terminal voltages corresponding to point A, B and C in Figure 2. The total resistance, R_t , which is the sum of R_o and R_p , at different temperature and DODs are shown in Figure 3.

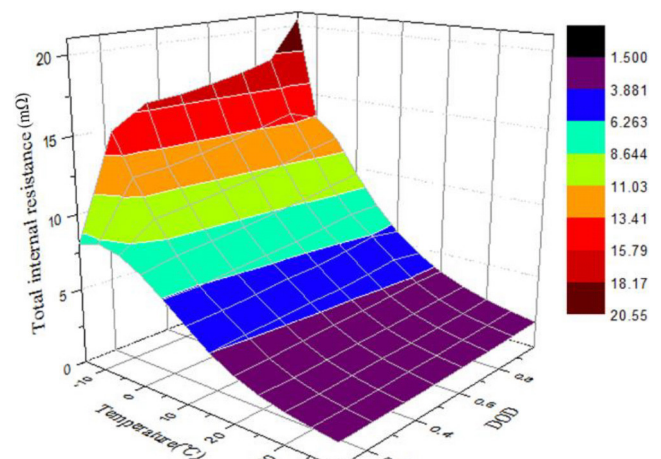


Figure 3. 3D surface diagram of internal resistance functions of temperature and DODs.

Entropy Coefficient

The entropy coefficient can be either achieved by measuring the battery open circuit voltage (OCV) variation with temperature at a fixed DOD, or determined based on the difference between heat generation during charging and discharging with an Accelerating Rate Calorimeter (ARC). According to Zhang et al. [11], the results achieved by these two methods are almost coincide to each other, but distinct in complexity and workload during the measuring process.

Because of the absence of a large-volume ARC for the 180 mm×100 mm×32 mm battery cell in measuring experiments, the OCV-temperature-variation method using a digital voltage meter (DVM, type: Agilent 34401A, basic measuring accuracy for direct-current voltage: 0.0015%) was applied in this work. The measuring process during discharge mainly consists of the following steps:

1. discharge the battery to a certain DOD;
2. keep the battery at a fixed temperature long enough until the OCV is stable (when $\partial E/\partial T < 0.1$ mV/min);
3. measure OCV with the DVM;
4. change the ambient temperature (at a temperature step of 5°C in a temperature range from -20°C to 40°C) and repeat step 2 and 3;
5. change DOD and repeat step 2, 3 and 4.

It is clear that the DVM-based method is an indirect way to calculate the entropy heat and the operation process might takes a long time to achieve the stable OCVs. In contrast, the ARC-based method is more easily to operate and also time-saving. However, a large-volume ARC is usually less accessible than a DVM with high precision. Thus, the DVM-based method is more often chosen in the entropy change measurement especially for power batteries with large volume and capacity. The measured entropy coefficient during discharge at different temperatures and DODs is shown in Figure 4.

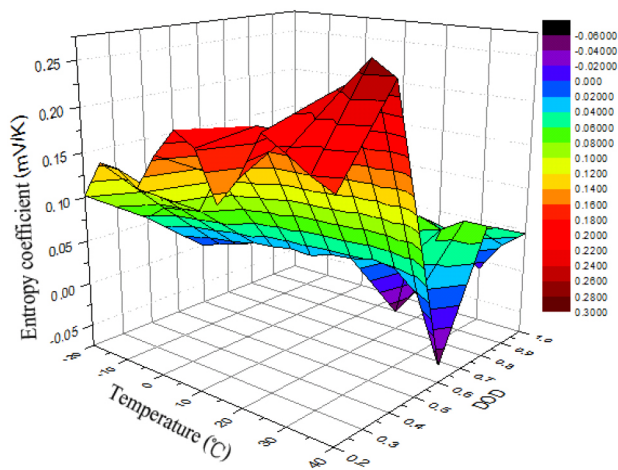


Figure 4. 3D surface diagram of entropy coefficient during discharge as functions of temperature and DODs.

Battery Heat Generation Rate

Measured internal resistance and entropy coefficient, as shown in Figure 3 and Figure 4, during different temperature ranges were fitted by using the 'polyfit' tool in 'Curve Fitting Toolbox' of MATLAB, and, thereby, these heat source terms at any DOD can be calculated based on the measured data. Taking the source terms of Rt and $\partial E/\partial T$ into Equation (2), cell heat generation rate at any discharge time can be calculated. The transformation from DOD in Eq. (2) to discharge time, t , is based on the following equations.

$$\text{DOD} = 1 - \frac{t_{\text{dis,ideal}} - t}{t_{\text{dis,ideal}}} \quad (5)$$

$$t_{\text{dis,ideal}} = 3600/C \quad (6)$$

where $t_{\text{dis,ideal}}$ is the ideal total discharge time, s; t represents any instantaneous time during discharge, s; C is the constant-current rate (in this work, $C=2, 3$).

Heat generation rates of the battery during 2C ($I=-80$ A) and 3C ($I=-120$ A) constant-current discharge processes are shown in Figure 5. It is worth noting that side reaction heat caused by phase changes, components decomposition and mixing effects is neglected in Equation (1), thus a scale factor of 1.2 is applied in the calculation of battery heat generation rate. The scale factor in thermal calculation is determined by experimental validation, as shown in Figure 6. The experimental and numerical profiles represent the battery surface temperature measured by a thermocouple in an approximately adiabatic environment and the numerical battery average temperature, respectively. Details of the experiments on battery thermal behavior during discharge are beyond the scope of this work and will not detailed here. According to the experimental data (as depicted in Figure 6 for 2C discharge), the discharge time $t_{\text{dis,real}}$ adopted in simulation in this work is smaller than the theoretical $t_{\text{dis,ideal}}$ in Equation (6).

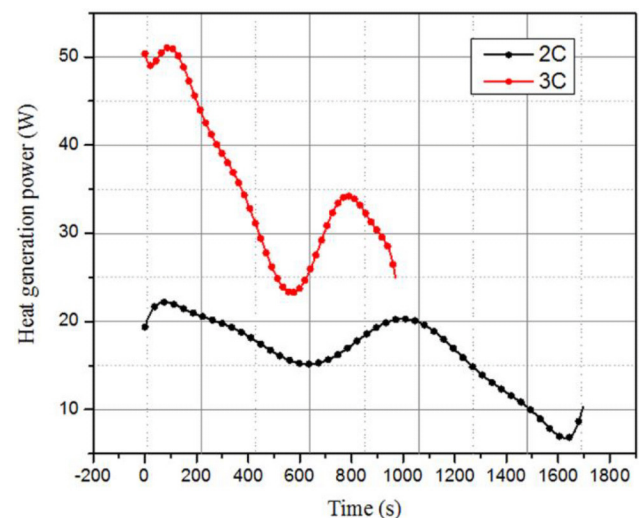


Figure 5. Heat generation rate as a function of discharge time.