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Experimental investigation on heat generation behaviors of the high-capacity lithium-ion battery with different charging conditions

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ABSTRACT

The charging/discharging characteristics of lithium-ion battery are mainly dependent on itself temperature which is determined by the balance both the heat generated by battery itself and the heat removed by the battery thermal management system (BTMS). Consequently, study on the heat generation behaviors of the lithium-ion battery is necessary for designing the BTMS which is capable of maintaining batteries at optimum temperature ranging from 20°C to 40°C. In this study, the heat generation behaviors and electro-thermal characteristics of a prismatic $LiFePO_4$ battery with a high nominal capacity of 280Ah at the charging rates of 0.5C and 1C and initial temperatures of 15°C, 25°C and 35°C were comprehensively explored using an electrochemical-calorimetric method. The experimental results show that the charging capacity at the end of charging is nearly independent on the above mentioned charging rates and initial temperatures, which is due to the positive effect of heat generated by the battery itself in accelerate calorimeter rate (ARC). However, it is noted that the heat generation rates during the charging process (especially for the beginning of charging) significantly increases with the growth of charging rate and the decrease of initial temperature. At the state of charge (SOC) equal to 0.1 and initial temperature of 15°C, the heat generation rates at charging rates of 0.5C and 1C are about 20.2 W and 76.6 W respectively, that is to say, the heat generation rate at high charging rate of 1C is nearly 3.8 times than that at moderate charging rate of 0.5C. These findings indicate that the battery own the excellent charging efficiency (short charging time and charging capacity nearly equal to nominal capacity) at the high charging rate of 1C, however, significant rise of heat generation rate inevitably brings the huge challenge for the BTMS. This study may also provide some guidance for the design of BTMS.

Keywords: lithium-ion battery, heat generation behaviors, electro-thermal characteristics, electrochemical-calorimetric method

NONMENCLATURE

Abbreviations	
ARC	Accelerating rate calorimeter
BTMS	Battery thermal management system
CC	Constant current
CV	Constant voltage
EVs	Electric vehicles
OCP	Open circuit potential
SOC	State of charge
Symbols	
T_{cell}	Battery surface temperature (°C)

1. INTRODUCTION

The rechargeable lithium-ion batteries have become the favored candidate for the power source of electric vehicles (EVs) due to their excellent overall performance, e.g., high power density, high discharging plateau, long cycling life and low self-discharging [1-2]. It is noted that high and low temperature would significantly affect the charging/discharging performance, cycling life and safety of the battery, especially for excessive high operating

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temperature which may result in an obvious degradation of battery capacity, thermal runaway or even fire hazard [3-4]. Some researches have showed that a proper-designed battery thermal management system (BTMS) enables to maintain the battery pack at the optimum temperature range of 20°C - 40°C, which can ensure the high efficiency and safety operation of the battery pack, further improving the overall performance of EVs [5-8].

The charging/discharging characteristics of lithium-ion battery are mainly dependent on itself temperature which is determined by the balance both the heat generated by battery itself and the heat removed by the battery thermal management system (BTMS). Consequently, study on the heat generation behaviors of the lithium-ion battery is necessary for designing the BTMS which is capable of maintaining batteries at optimum temperature ranging from 20°C to 40°C.

In this study, the heat generation behaviors and electro-thermal characteristics of a prismatic $LiFePO_4$ battery with a high nominal capacity of 280Ah at the charging rates of 0.5C and 1C and initial temperatures of 15°C, 25°C and 35°C were comprehensively explored using an electrochemical-calorimetric method. This study aims to provide some guidance for the design of BTMS.

2. EXPERIMENTAL SETUP AND MEASUREMENT

The heat generation behaviors of a prismatic lithium-ion battery with a high nominal capacity of 280Ah at the charging rates of 0.5C and 1C and initial temperatures of 15°C, 25°C and 35°C were explored using an electrochemical-calorimetric method. According to the definitions of C-rate, the charging currents for 0.5C and 1C are 140A and 280A, respectively. The technical parameters of the lithium-ion battery used in this study are summarized in Table 1. The schematic diagram of the experimental setup showing the connection line among the battery, the battery cycler (NEWARE) and the accelerating rate calorimeter (EV+ARC) is also illustrated in Fig. 1. Note that the positive and negative terminals of the studied battery were connected with the battery cycler to measure the charging capacity and terminal voltage. Meanwhile, the battery was put into the calorimetric chamber of EV+ARC in order to explore the heat generation behaviors under the adiabatic condition.

Table 1 Parameters of the tested battery

Parameter	Value
Rated capacity (Ah)	280
Nominal voltage (V)	3.2
Charge cut-off voltage (V)	3.65
Discharge cut-off voltage (V)	2.5
Cathode material	$LiFePO_4$
Anode material	Graphite
Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	933
Battery mass (g)	5510

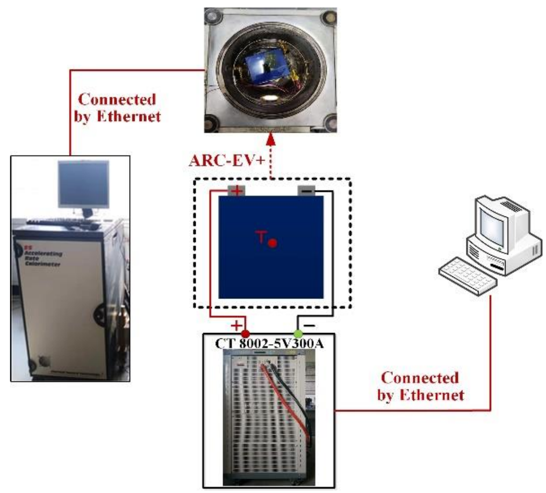


Fig. 1 Schematic diagram of the experimental setup.

3. RESULTS AND DISCUSSION

3.1 Analysis of electro-thermal characteristics

The charging scheme of the tested battery under the three initial temperatures of 15°C, 25°C and 35°C is identical, which is constant current and constant voltage (CC-CV) charging regime. Specifically, the tested battery is charged at constant current (CC) regimes of 0.5 C and 1C in respective until the terminal voltage reaches 3.65 V, and then charged at a constant voltage (CV) regime of 3.65 V until the current is below 14 A.

The charging curve and battery surface temperature of the tested battery at charging regime of 0.5C and initial temperature of 15°C are illustrated in Fig. 2. It is observed that the terminal voltage remarkably increases at the beginning of CC regime mainly caused by the ohmic resistance, and then almost remains constant along the main charging process, and increases sharply again at the end of CC regime due to the rapid increase of overpotential resistance. Subsequently, the terminal voltage reaches 3.65 V until the transition point (B), while the terminal voltage is held at 3.65 V during CV regime (between B and C). During the resting process, the terminal voltage of the tested battery gradually decreases because of the reduction of overpotential resistance. As expected, the battery surface temperature gradually increases and reaches the maximum value until the terminal point (C) of charging test, and then keeps constant during the resting process which indicates that the ARC owns excellent thermal insulation performance. Specifically, the temperature rises at CC regime and CV regime are 25.3°C and 1.3°C, which accounts for 95.1%, 4.9% of the whole charging process respectively. These results indicate that the temperature rise at the CV regime could be neglected during the whole charging process (CC regime and CV regime).

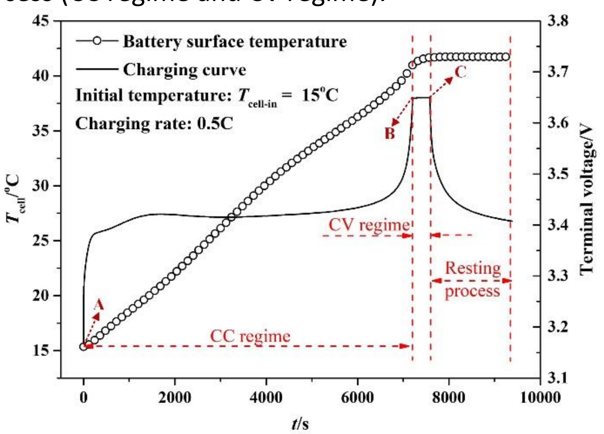
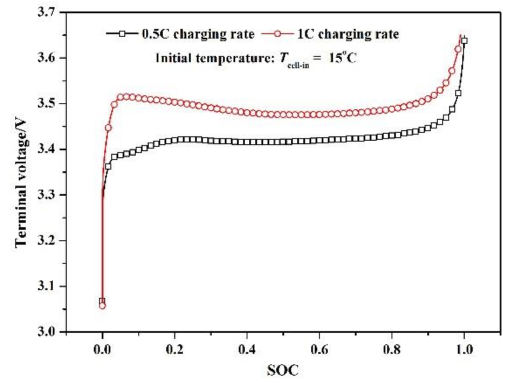


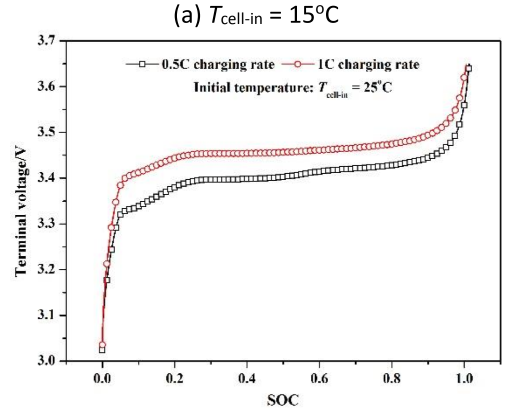
Fig. 2 Battery surface temperature and charging curve of the tested battery at the initial temperature of 15°C and charging rate of 0.5C.

In the light of the above analysis, the electro-thermal characteristics of the tested battery at the CC regime under the charging rates of 0.5C and 1C and initial temperatures of 15°C, 25°C and 35°C were explored in detail and shown in Fig. 3 and Fig. 4. In the case of any given initial temperatures, it is found that the terminal voltages at high charging rate (1C) are obviously higher than that at moderate charging rate (0.5C) during the charging process. Interestingly, the charging capacity at the end of charging is nearly independent on the above mentioned charging rates and initial temperatures, which is due to the positive effect of heat generated by the battery itself in ARC. In addition, the terminal voltage differences of the tested battery between 0.5C and 1C have a slight reduction with the increase of initial temperature. For instance, at the SOC equal to 0.1, the above mentioned terminal voltage differences at three initial temperatures of 15°C, 25°C and 35°C are 0.11V, 0.07V and 0.06V respectively. It is observed from Fig. 4 that the differences of battery surface temperature of the tested battery between 0.5C and 1C are 13.6°C, 8.9°C and 9.1°C at the end of charging, which are resemblance to the variations of terminal voltage difference in the range of 15°C to 35°C.

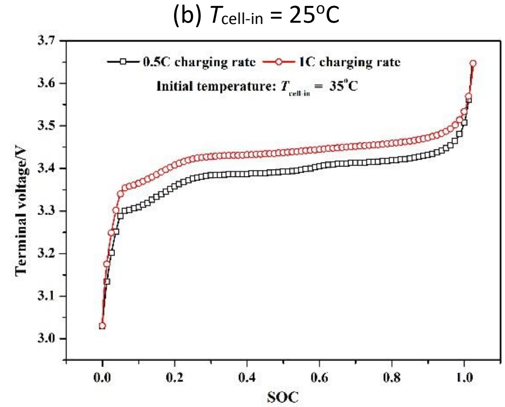
The above results certainly demonstrate that although the charging capacities at the end of charging are nearly independent on the charging rates ranging from 0.5C to 1C and the initial temperatures ranging from 15°C to 35°C, there are also differences in the electro-thermal characteristics of the $LiFePO_4$ battery which would affect its heat generation behavior to some extent (discussed in Section 3.2).



(a) $T_{cell-in}$ = 15°C

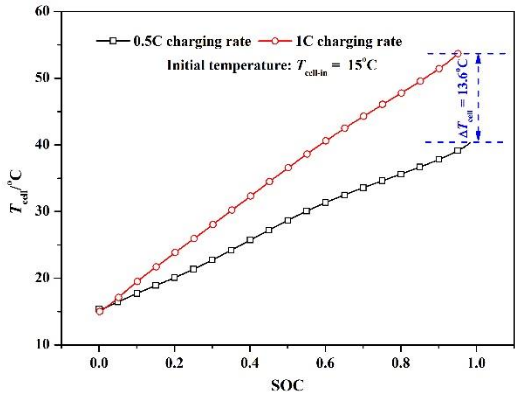


(b) $T_{cell-in}$ = 25°C

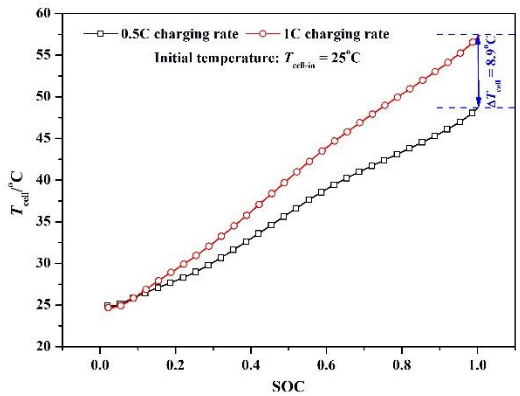


(c) $T_{cell-in}$ = 35°C

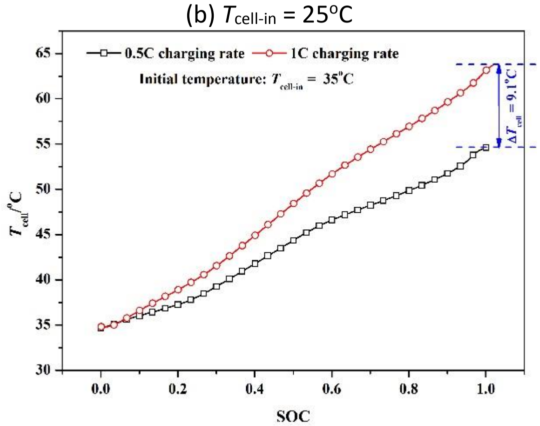
Fig. 3 Charging curves of the tested battery in ARC under three initial temperatures of 15°C, 25°C and 35°C.



(a) $T_{cell-in}$ = 15°C



(b) $T_{cell-in}$ = 25°C



(c) $T_{cell-in}$ = 35°C

Fig. 4 Battery surface temperatures of the tested battery in ARC under three initial temperatures of 15°C, 25°C and 35°C.

3.2 Analysis of heat generation behaviors

The heat generation rate and charging curve of the tested battery at charging regime of 0.5C and initial temperature of 15°C are shown in Fig. 5. The charging curve would be employed to intuitively evaluate the variation of heat generation rate. It is observed that the heat generation rate remarkably increases at the beginning and end of CC regime, which is resemblance to the variation of terminal voltage caused by the ohmic and overpotential resistances. In addition, we find that the heat generation rate drops sharply during the CV regime and finally equals to 0 W during the resting process. This phenomenon is mainly caused by an obvious reduction of charging currents. Noting that there is a relatively obvious fluctuation in the heat generation rate along the main charging process, which is different from variation of terminal voltage (almost remains constant). The reason is that the heat generation rate depend on not only the terminal voltage (affecting the irreversible heat), but also the temperature coefficient of OCP (affecting the reversible heat).

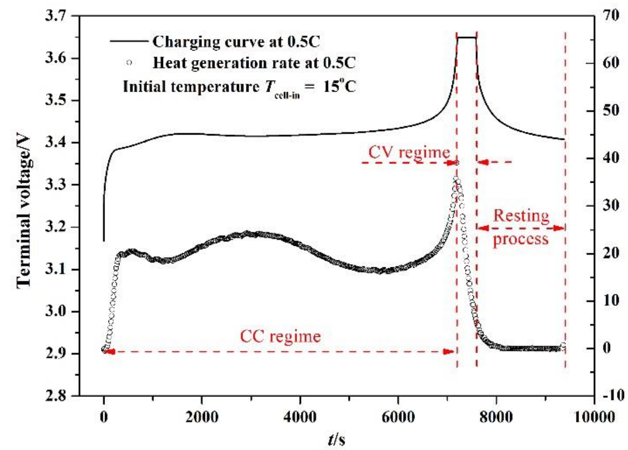
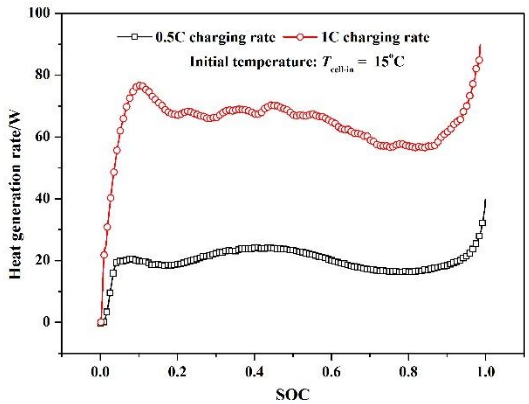


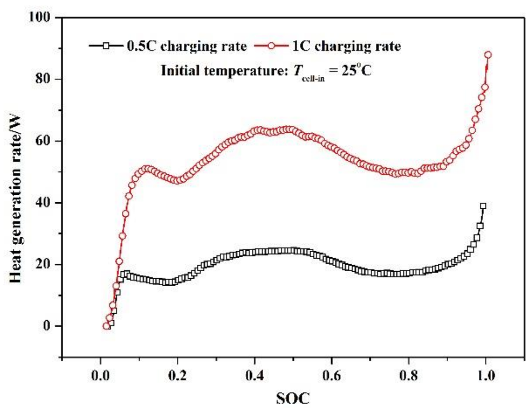
Fig. 5 Heat generation rate and charging curve of the tested battery at the initial temperature of 15°C and charging rate of 0.5C.

As expected, it is observed from Fig. 6 that the heat generation rate at higher charging rate (1C) is remarkably higher than that at moderate charging rate (0.5C) in the case of any given initial temperatures. Taking example from a SOC of 0.1 and an initial temperature of 15°C, the heat generation rates at charging rates of 0.5C and 1C are about 20.2 W and 76.6 W respectively, that is to say, the heat generation rate at high charging rate of 1C is nearly 3.8 times than that at moderate charging rate of 0.5C. Combined with the electro-thermal characteristics discussed in Section 3.1, we conclude that the battery could own the excellent charging efficiency (short charging time and charging capacity nearly equal to nominal capacity) at the higher charging rate of 1C, however, significant rise of heat generation rate inevitably brings the huge challenge for the BTMS.

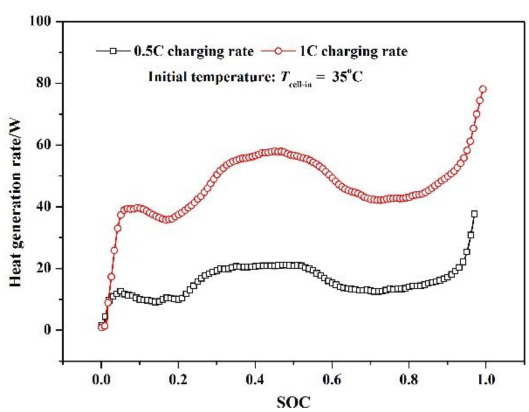
Figure 7 shows the comparison of heat generation rates at 1C under the three initial temperatures of 15°C, 25°C and 35°C. It is found that the heat generation rates gradually increase with decreasing temperatures along the main charging process, while the heat generation rates according to the different initial temperatures (15°C, 25°C and 35°C) have a slight difference at the end of charging process. This phenomenon could be mainly attributed to the obvious temperature rise resulted from the heat generated by battery itself at the end of charging process, which enables to eliminate the negative effect of lower initial temperature on the chemical metabolism.



(a) $T_{\text{cell-in}}$ = 15°C



(b) $T_{\text{cell-in}}$ = 25°C



(c) $T_{\text{cell-in}}$ = 35°C

Fig. 6 Heat generation rates of the tested battery at charging rates of 0.5C and 1C as well as initial temperatures of 15°C, 25°C and 35°C.

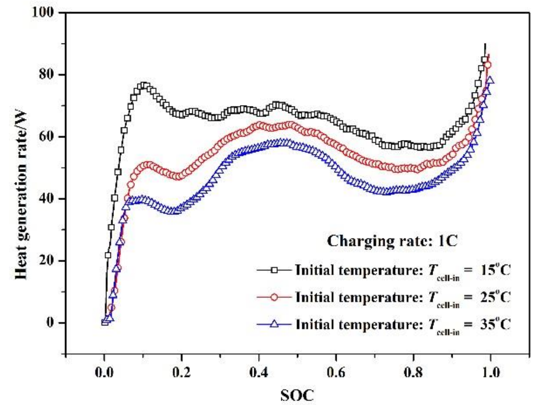


Fig. 7 Comparison of heat generation rates of the tested battery at 1C under three initial temperatures of 15°C, 25°C and 35°C.

4. CONCLUSIONS

In this study, the heat generation behaviors and electro-thermal characteristics of a prismatic lithium-ion battery with a high nominal capacity of 280Ah at the charging rates of 0.5C and 1C and initial temperatures of 15°C, 25°C and 35°C were comprehensively explored using an electrochemical-calorimetric method. The experimental results showed that the charging capacity at the end of charging is nearly independent on the charging rates (0.5C and 1C) and initial temperatures (15°C, 25°C and 35°C). In addition, it is found that the heat generation rates during the charging process (especially for the beginning of charging) significantly increases with the growth of charging rate and the decrease of initial temperature. At the SOC of 0.1 and initial temperature of 15°C, the heat generation rates at two charging rates of 0.5C and 1C are about 20.2 W and 76.6 W respectively. These findings indicate that the battery own the excellent charging efficiency (short charging time and charging capacity nearly equal to nominal capacity) at the high charging rate of 1C, however, significant rise of heat generation rate inevitably brings the huge challenge for the BTMS.

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