Internal Heat Self-generation in LiFePO_4 Battery Module

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Dae Hyun Jung^a, Dongmin Kim^a, Sang-il Kim^b, and TaeWan Kim^{a,*}

^aDepartment of Electrical Engineering and Smart Grid Research Center, Jeonbuk National University, Jeonju 54896, Republic of Korea

^bDepartment of Materials Science and Engineering, University of Seoul, Seoul 02504, Republic of Korea

*Corresponding author E-mail: twkim@jbnu.ac.kr

ABSTRACT

Currently, lithium-ion batteries (LIBs) are widely used in electric vehicles and renewable energy systems, which require substantial energy storage capacities. Although the LIB has the advantages of enhanced energy efficiency and power density, thermal runaway and the ensuing degradation of the batteries are challenges that remain. The effects of self-generated heat include reduced lifespan of the LIB and thermal runaway in the module configuration owing to unreleased heat from the boundary of neighboring cells. In this study, a spatial resolution temperature monitoring system was employed to investigate the self-generated heat of a LiFePO_4 -based LIB module. The investigations revealed that there is a significant increase in the surface temperature as well as in the difference between surface and internal cell temperatures, with increasing charge-discharge rates in the range of 0.2–2 C (14–140 A). Furthermore, the temperature increases of LIB modules were higher at high discharge rates above 0.7 C (49 A) and lower at relatively low discharge rates such as 0.2 C (14 A) and 0.5 C (35 A).

Keywords: Lithium-ion battery module, Heat self-generation, Temperature monitoring

1. Introduction

Renewable energy generation systems and electric vehicles require energy storage systems (ESS) to store the surplus electricity, due to the timing imbalance in electricity production and consumption. The lithium-ion battery (LIB), a battery that comprises of the ESS, with high energy-density and no memory effect, is widely used in a modularized form [1,2]. The LIB generates heat due to the electrochemical reaction during the charge/discharge process [3]. The reasons for the heat generated during the charge/discharge of a lithium-ion battery can be divided into reversible and irreversible processes relating to the chemical reaction and charge transfer during the charge/discharge [4]. The heat generated during the reversible process, also called entropy heat, results from the reversible change in entropy throughout the electrochemical reaction [5], while the irreversible process involves the active polarization phenomenon, ohmic heating, and change in enthalpy [6,7]. The polarization phenomenon occurs due to the over-voltage between the battery operating potential and the open circuit potential. It makes an increase of the charge transfer resistance of the Solid Electrolyte Interphase (SEI) that forms on the surface of the anode when the electrode-electrolyte interface (or anode and cathode), formed by oxidation during charge/discharge, makes contact with the electrolyte and the electrolyte breaks down. Heat is generated as the lithium-ion overcomes the resistance of each interface during the intercalation/deintercalation processes [8,9]. Ohmic heating occurs at both electrode and electrolyte due to the electrode and electrolyte resistance that hampers charge transfer [10]. Lastly, enthalpy change, another type of irreversible heat-generating process, is mostly caused

by the phase change of the anode and the cathode due to the spread of lithium ions [11]. The self-generated heat during the charge/discharge process of a lithium-ion battery not only degrades the battery's performance but also leads to potential safety problems [12]. Therefore, heat generation is a significant issue while operating the lithium-ion battery in a high-temperature environment or at rapid charge/discharge rates. In the case of LiCoO_2 and LiMn_2O_4 lithium-ion battery cells, the battery capacity drops drastically due to crystallographic change by heat during charge/discharge, and the $\text{Li}(\text{Ni}, \text{Mn}, \text{Co})\text{O}_2$ based lithium-ion battery cell showed 7.5 and 22 % decrease in battery capacity at 85 and 120 °C, respectively, due to a binder and SEI deformation [13,14]. Although there are many studies that focus on the effects of self-heat generation during charge/discharge in cell units of lithium-ion batteries, not many studies on self-heat generation during charge/discharge in battery module units are available [15,16]. The partial heat generation at the boundary between the modules may be different from that between the battery cell units; furthermore, the temperature deviation among modules may be higher than the temperature deviation among the unit cells depending on the spatial arrangement. This leads to critical impacts on the performance and stability of the battery module.

In this study, eight 70 Ah prismatic type LiFePO_4 /graphite cells were connected in series to construct a module, and eight temperature sensors (channel 1–channel 8) were installed inside and outside the module at different spatial locations to measure the temperature of the module under various charge/discharge conditions. Then, the distribution of temperature due to self-generated heat at different points in the battery module, during the charge/discharge, based on the measurements

from the spatially distributed sensors was identified.

2. Materials and methods

The specifications of the battery cell used in this study is listed in Table I. Eight cells were connected in series to form a battery module. The power conversion system (PCS) from BaSyTec and the heat flow logger LR8431 from Hioki were used to organize a battery charge/discharge and spatial-resolution temperature sensing system, as shown in Fig. 1. The maximum output of the PCS was 4.5 kW, 70 V, 210 A, and the heat flow logger measured the temperature generated within the battery module during the charge/discharge via PCS to analyze the temperature distribution. Eight k-type thermocouple temperature

Table I. Specifications of the Li-ion battery.

Items	Specifications
Type specification	IFP36115200
Upper limit voltage	3.65 V
Lower limit voltage	2.5 V
Norminal voltage	3.2 V
Rated capacity	70 Ah
Series	Prismatic cell
Length	200.0 mm $\pm$ 0.3 mm
Width	115.2 mm $\pm$ 0.5 mm
Thick	36.2 mm $\pm$ 0.3 mm

Figure 1. Battery charge/discharge temperature measurement system diagram.

Figure 2. Schematic of battery module structure and temperature sensor positions.

sensors (channel 1-channel 8) were placed, as shown in Fig. 2, to analyze the temperature distribution inside the battery module. Channel 1-channel 4 were placed within the module between cells, and channel 5-channel 8 were placed on the module surface. Charge/discharge-voltage range was set to 24–28 V, and charge/discharge speeds (current) were set to 0.2 C (14 A), 0.5 C (35 A), 0.7 C (49 A), 1 C (70 A), 1.5 C (90 A), and 2 C (140 A).

Each experiment was performed at room temperature and atmospheric pressure. There were 10 cycles of charge/discharge, and there was a 30-min break between each charge and discharge cycle for stability.

3. Results and discussion

Figure 3 shows the change in voltage and temperature (channel 1-channel 8) during 10 cycles of charge/discharge rates at 0.2 C, 0.5 C, 0.7 C, 1 C, 1.5 C, and 2 C, as the temperature distribution inside and outside the battery module. Figure 3 also shows the self-generated heat within the battery module during charge/discharge by spatial location.

At 0.2 C charge rate, the highest temperature was 31.7 °C at channel 1 and channel 2, whereas the lowest temperature was 30.4 °C at channel 5, showing a difference of approximately 1.3 °C. At a rate of 0.5 C, the highest and lowest inner and outer temperatures were 38.9 and 35.7 °C, respectively, with approximately 3 °C temperature difference. Similarly, at 0.7 C, the inner and outer temperatures were 43.2 and 38.5 °C with approximately 4–5 °C temperature difference. Furthermore, at charge rates over 1 C, the difference between inner and outer temperatures increased even more so much so that at a rate of 2 C, the module's highest internal temperature during the charge/discharge was 61.9 °C, while the surface temperature (channel 7) was 51.2 °C, notably confirming that a significant temperature difference of approximately 10.7 °C occurred.

Figure 3. Charge/discharge curves of voltage and temperature (Ch.1–Ch.8) with time at different charge/discharge rates: (a) 0.2 C; (b) 0.5 C; (c) 0.7 C; (d) 1 C; (e) 1.5 C; (f) 2 C.

Figure 4. Max, min, and average temperatures at different charge-discharge rates: 0.2 C; 0.5 C; 0.7 C; 1 C; 1.5 C; 2 C.

Figure 5. Magnified charge/discharge curves of voltage and temperature (Ch.1–Ch.8) with time at different charge/discharge rates: (a) 0.2 C; (b) 0.5 C; (c) 0.7 C; (d) 1 C; (e) 1.5 C; (f) 2 C.

Figure 4 shows the temperature distribution summary in the charge/discharge range of 0.2–2 C. It expresses the highest temperature, lowest temperature, and the average temperature of all channels graphically. As shown in Figs. 3 and 4, as charge/discharge rate increases, the temperature difference and average temperature both rise across all spatial locations. This is because the low heat transfer efficiency of the material makes it difficult to release the inner heat generated at the boundary between the cells. The high temperature generated inside may critically influence the stability of the battery module as well as cause its degradation. The spatial temperature distribution may vary with variations in cell distancing in the battery module, module organization, and cooling method; as such a new battery module structural design is needed to solve the problems

mentioned above [17].

Figure 5 is the magnified version of Fig. 3. For every charge/discharge rate (0.2–2 C), a temperature increase due to the exothermic reaction during the charging process was observed. Interestingly, while the discharging process involved both endothermic and exothermic reactions at discharge rates of 0.2–1 C, the exothermic reaction was more dominant at rates of 1.5–2 C. This is because the reversible and irreversible processes determine the battery's endothermic and exothermic reactions respectively and the irreversible process takes a dominant role as the magnitude of current increases [18]. Therefore, in the 1.5–2 C discharge rate range, where relatively high current flows during the charge/discharge process, only the exothermic reaction is observed.

4. Conclusions

Analyzing the self-generated heat of a lithium-ion battery module during charge/discharge is essential for predicting the degradation and life span of the battery and determining the thermal stability of cathode material. Unlike cells, the difference in temperature between the inside and the surface at any spatial location, may occur to a more significant degree in a module. This paper established the spatial distribution of temperature and the surface to internal temperature difference in a lithium-ion battery module by connecting eight prismatic type LiFePO₄/graphite cells in series and conducting 10 cycles of trials under various charge/discharge conditions. Typically, the highest temperature occurred inside the battery module between the cells, and the lowest temperature occurred on the outer surface of the module. As the charge/discharge rate increased, temperatures and temperature differences increased. Remarkably, at a discharge rate of 2 C, the most significant inner and outer temperature difference of approximately 10.7 °C was observed with inner and surface temperatures of 61.9 and 51.2 °C, respectively. The temperature difference is higher at faster charge/discharge rates because of an increase in irreversible heat generation and unreleased heat due to short distance between cells. Therefore, if the outer surface temperature of the LIB modules is considered as the temperature of the entire module for various applications of the LIB, it will introduce errors in the prediction of the battery life and also make it difficult to secure the safety of the battery.

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References

- [1] A. Khaligh and Z. Li, *IEEE Trans. Veh. Technol.* 59, 2806 (2010).
- [2] T. Sasaki, Y. Ukyo, and P. Novák, *Nat. Mater.* 12, 569 (2013).
- [3] G. Liu, M. Ouyang, L. Lu, J. Li, and X. Han, *J. Therm. Anal. Calorim.* 116, 1001 (2014).
- [4] W. Lu and J. Prakash, *J. Electrochem. Soc.* 150, A262 (2003).
- [5] V. V. Viswanathan, D. Choi, D. Wang, W. Xu, S. Towne, R. E. Williford, J. Zhang, J. Liu, and Z. Tang, *J. Power Sources* 195, 3720 (2010).
- [6] L. Song, Z. Xiao, and Y. Zhou, *Electrochim. Acta.* 114, 611 (2013).
- [7] A. Nazari and S. Farhad, *Appl. Therm. Eng.* 125, 1501 (2017).

- [8] A. Nyman, T. G. Zavalis, R. Elger, M. Behm, and G. Lindbergh, *J. Electrochem. Soc.* 157, A1236 (2010).
- [9] M. Nie, D. Chalasani, D. P. Abraham, Y. Chen, A. Bose, and B. L. Lucht, *J. Phys. Chem. C* 3, 1257 (2013).
- [10] M. Xiao and S. Y. Choe, *J. Power Sources* 241, 46 (2013).
- [11] J. Esmaili and H. Jannesari, *Energy Convers. Manage.* 139, 194 (2017).
- [12] F. Leng, C. M. Tan, and M. Pecht, *Sci. Rep.* 5, 1 (2015).
- [13] H. Gabrisch, Y. Ozawa, and R. Yazami, *Electrochimica. Acta.* 4, 1499 (2006).
- [14] L. Bodenes, R. Naturel, H. Martinez, R. Dedryvère, M. Menetrier, L. Croguennec, J. P. Pérès, C. Tessier, and F. Fischer, *J. Power Sources* 236, 265 (2013).
- [15] L. Song, Z. Xiao, L. Li, and Q. Zhou, *J. Solid State Electrochem.* 19, 2167 (2015).
- [16] C. Lin, F. Wang, B. Fan, S. Ren, Y. Zhang, L. Han, S. Liu, and S. Xu, *Energy Procedia.* 142, 3369 (2017).
- [17] C. F. Lopez, J. A. Jeevarajan, and P. Mukherjee, *J. Electrochem. Soc.* 162, A1905 (2015).
- [18] L. Song, X. Li, Z. Wang, X. Xiong, Z. Xiao, and F. Zhang, *Int. J. Electrochem. Sci.* 7, 6571 (2012).