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Experimental Analysis on the Thermal Management of Lithium-Ion Batteries Based on Phase Change Materials

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Received: 10 September 2020; Accepted: 19 October 2020; Published: 21 October 2020

Abstract: Temperature is an important factor affecting the working efficiency and service life of lithium-ion battery (LIB). This study carried out the experiments on the thermal performances of Sanyo ternary and Sony LiFePO₄ batteries under different working conditions including extreme conditions, natural convection cooling and phase change material (PCM) cooling. The results showed that PCM could absorb some heat during the charging and discharging process, effectively reduce the temperature and keep the capacity stable. The average highest temperature of Sanyo LIB under PCM cooling was about 54.4 °C and decreased about 12.3 °C compared with natural convection in the 2 C charging and discharging cycles. It was found that the addition of heat dissipation fins could reduce the surface temperature, but the effect was not obvious. In addition, the charge and discharge cycles of the two kinds of LIBs were compared at the discharge rates of 1 C and 2 C. Compared with natural convection cooling, the highest temperature of Sanyo LIB with PCM cooling decreased about 4.7 °C and 12.8 °C for 1 C and 2 C discharging respectively, and the temperature of Sony LIB highest decreased about 1.1 °C and 2 °C.

Keywords: lithium-ion battery; thermal management; phase change material; temperature; heat dissipation fins; capacity

1. Introduction

The ways to deal with the energy crisis and environmental pollution and develop new energy of safety and cleanness have become the focus of the attention of all countries in the world. It also becomes the core issue to solve the sustainable development of humankind. LIBs, which have the advantages of high specific energy, relatively high operating voltage, long cycle life, low self-discharge rate, small and convenient, are considered to be one of the most promising energy storage devices [1–3]. However, if the operating temperature of LIB is high and the heat dissipation is not timely, it will lead to thermal failure, shorten the service life of LIB and cause safety problems, such as fire and explosion [4,5]. Therefore, the thermal safety of LIB needs to be focused on.

The temperature difference between battery internal and ambient, as well as the temperature difference between the cells inside the battery pack will have a negative impact on the performance, life and safety of the battery [6]. Therefore, it is necessary to conduct a reasonable heat management system to make the LIB working in the normal operating temperature range [7–10]. At present, there are three kinds of mainstream thermal management methods for LIBs including air cooling, liquid cooling

and PCM cooling [11]. Air cooling is divided into natural air cooling and forced air cooling. Pesaran et al. studied the air cooling performance of the battery thermal management system (BTMS). The results showed that the air cooling could effectively reduce the battery temperature and keep the battery temperature consistent in a low rate discharging [12]. Giuliano et al. studied the thermal management system using air cooling of metal foam-based heat exchanger plate. The system showed that the LIB temperature decreased with the increase of airflow. However, the thermal conductivity of air is low and the heat dissipation is weak [13]. Compared with the air cooling method, the liquid cooling method has higher thermal conductivity, which leads to higher cooling performance and is more suitable for cooling large battery packs. Liquid cooling is divided into direct and indirect liquid cooling. Chen et al. compared different liquid cooling systems of LIB, and the results showed that the indirect liquid cooling system had the lowest temperature rise and was more practical than direct liquid cooling [14]. Zhang et al. applied the S-type guide plate to the integrated module of liquid cooling heat dissipation system, and found that the device could avoid heat concentration, improve heat transfer performance and keep the temperature of LIB uniform [15]. However, the traditional battery thermal management method that uses cheap air and water as the cooling medium requires additional energy to drive the cooling medium circulation. In battery thermal management applications, the battery's safe operating temperature is often sacrificed at the expense of battery capacity and power in exchange for longer operating life, and these traditional thermal management methods are complex and occupy a large space [16]. In recent years, researchers have found that PCMs exhibit excellent performance in thermal management of LIB [17,18] since they have large storage density apart of many other advantages [19–21]. Duan et al. conducted the numerical and experimental studies on PCM heat transfer, and found that they have great potential in thermal management due to potential energy storage and controllable temperature stability [22]. PCM battery management system which performed better than traditional thermal management system was first proposed and patented by Al-Hallaj and Selman [23,24]. Mills and Al-Hallaj used the entropy coefficient method to simulate the battery pack, and the results showed that using a PCM could significantly improve the system performance and keep the operating temperature below 55 °C, even at high discharge rate [25]. Javani et al. studied the effect of a PCM on LIB, and found that it could make the temperature distribution uniform and keep the battery in a safe temperature range [26]. Weng et al. systematically investigated the cooling behavior and the influence of several detailed factors on the performance of a PCM. The experimental results showed that a PCM module with a thickness of ~10 mm presented the optimal cooling performance [27]. Javani et al. investigated the heat transfer with a PCM in passive thermal management of electric and hybrid electric vehicles. The results showed that the temperature distribution became about 10% more uniform when a PCM was applied in a 3 mm thickness around the cell. The PCM with 12 mm thickness decreased the maximum temperature about 3.04 °C [28]. However, it is found that PCM is easy to get heat saturation when absorbing a large amount of heat in the practical application. BTMS based on pure phase-varying materials cannot work for a long time in high-power batteries and effectively control the battery temperature. Commonly used PCM is paraffin wax whose thermal conductivity is very low. The thermal conductivity of PCM is improved by adding high thermal conductivity materials such as expanded graphite, carbon fiber, graphene, aluminum foam, copper foam and so on [29–32].

On the other hand, many researchers combined other cooling methods with PCM-based BTMS in order to improve the cycling stability and thermal management ability [33,34]. The complex PCM based BTMS can effectively reduce temperature rise and temperature difference, and maintain battery performance, particularly in extreme environments [35,36]. Sun et al. proposed a PCM combined with heat-dissipating fins to enhance the heat transfer. The results showed that the performance of PCM-fin system was better than that of pure PCM system [37]. Azizi et al. used a PCM and composite materials of aluminum mesh plates to carry on the thermal management to the LiFePO_4 battery pack under the high temperature environment. The results showed that the usage of PCM and aluminum wire mesh could significantly reduce the surface temperature of the batteries and improve the performance of the battery pack [38]. Although the use of PCM either alone or combined with heat dissipation fins had

been extensively studied, there is no optimal solution for the best cooling effect, quantity, and price of PCMs used in LIBs at present. The combination of a PCM and heat dissipation fin will inevitably increase the weight of the BTMS device. As far as we know, a PCM with high thermal conductivity in the battery charging and discharging cycles and the optimization of the coexistence system of PCM and heat dissipation fin also needs further research. In this paper, we first tested the cooling effect of a PCM with higher thermal conductivity whose phase change process is a solid-solid phase change, and then designed a new type of heat dissipation fins. The main purpose of this paper is to study the cooling effect of a PCM with high thermal conductivity on the battery and the effect of a PCM combined with a new type of heat dissipation fins with a relatively small volume. The authors conducted the experiments to investigate the temperature and capacity changing of two kinds of batteries under different conditions.

2. Experiment

2.1. Experimental Description

Experiments were carried out on two different brands of LIB (Sanyo ternary and Sony LiFePO_4 battery). The detailed parameters of the batteries were shown in Table 1. The experimental conditions of the battery in extreme conditions (inside the closed aluminum tube), natural convection, pure PCM, and PCM combined with the heat dissipation fins were set up. The experiments were carried out in the carton box (length $\times$ width $\times$ height, $35 \times 20 \times 20$ cm) for the thermal isolation from environmental influences, and each experimental condition is shown in Figure 1. The aluminum tube size with an inner diameter of 36 mm, the height of 65 mm, and thickness of 6 mm (provided by Yuezhong Metal Material Co., Ltd., Dongguan, China) was used, and its thermal conductivity is $237.2 \text{ W/m}\cdot\text{K}$. Figure 1d shows that the fin is composed of two circular fins and three vertical fins. Its material is tin sheet and the thermal conductivity is $150 \text{ W/m}\cdot\text{K}$. The design of the fin structure is followed by: (1) The ring is set at the bottom of the battery and in the middle of the battery respectively as the temperature of the middle and low part of the battery is higher. (2) The vertical fin protruding is designed to disperse the generated heat in time and reduce the temperature effect. (3) According to previous studies, the best results are obtained when the distance between the radiator and the battery is 0.2 times the diameter of the battery [39]. So, the circular heat dissipation fin size (outer diameter $\times$ inner diameter $\times$ height) is $\varnothing 26 \times \varnothing 22 \times 4$ mm, vertical heat dissipation fin size (length $\times$ width $\times$ height) is $4 \times 2 \times 80$ mm.

The high thermal conductivity phase change composites with phase change temperature of 52°C (provided by Zhongjia New Material Technology Co., Ltd., Guangzhou, China) were selected due to the higher thermal conductivity than the pure paraffin. In this experiment, the phase change material is wrapped around the battery with a thickness of 9 mm and a weight of about 9.9 g. The main components are phase change wax and expanded graphite, which have the following advantages: solid-solid phase change, high phase change latent heat, insulation, good cycle stability, non-corrosive, and non-toxic. Detailed thermal physical properties are shown in Table 2.

Table 1. Detailed battery parameters.

Battery Type	Sanyo Lithium-Ion Battery	Sony Lithium-Ion Battery
Capacity	2600 mAh	1100 mAh
Voltage (V)	3.7 V (Discharge cut-off voltage 3.0 V, The maximum charging voltage is 4.2 V)	3.2 V (Discharge cut-off voltage 2.0 V, The maximum charging voltage is 3.6 V)
Sizes	$\Phi 18 \times 65$ mm	$\Phi 18 \times 65$ mm
Life (seconds)	1000	1000
Anode material	Ternary materials	LiFePO_4

Figure 1. Experimental conditions

Table 2. Thermal physical properties of PCM.

Thermal Physical Characteristic	Parameters
Phase change temperature (°C)	52~55
Thermal conductivity (W/m·K)	3
Latent heat of phase change (J/g)	170
Specific heat capacity (J/kg·°C)	1.8
Density (g/cm ³)	0.2
Materials	Phase change wax, Expanded graphite

2.2. Experimental Facility

Figure 2 shows the schematic diagram of the experiments. The LIB charging and discharging instrument (provided by Neware Electronics Co., Ltd., Shenzhen, China) is provided for the LIB normal charging and discharging cycles, and the accuracy and stability of the whole range can reach 0.1%. The LIB temperature was measured by T-type thermocouples (provided by OMEGA), and recorded by the temperature data acquisition unit (provided by National Instruments) as shown in Figure 2. According to the factory temperature check, the thermocouple temperature measurement accuracy is controlled within 0.5 °C. The thermocouple is patch type, which is attached to the middle of the battery surface. The PCM is wrapped around the battery, and the thermocouple is embedded in the PCM. The thermocouple was calibrated before the experiments. The temperature of the LIB by thermocouple was measured only to analyze the cooling effect of PCM on the LIB, not to study the internal reaction of the LIB in this study. Hence, the T-type thermocouple is attached to the center position of the batteries surface to measure the optimum temperature.

Figure 2. Schematic diagram of the experiment.

Before the experiment, the LIBs were discharged to the cut-off voltage, charged to maximum voltage, and then placed 24 h to keep the LIB stable. The temperature in the carton is 25 °C, and its environmental temperature error is controlled within the normal range of 0.5 °C. The charge and discharge process of the two batteries are shown in Table 3. The cycle of Sanyo LIB can be divided into four stages: (1) discharge stage, with 2 C constant current discharge to 2.5 V. (2) shelving stage for 5 min. (3) charging stage with 1 C constant current and voltage to 4.2 V. (4) shelving stage with 5 min. The Sony LIB is tested in the same charge-discharge cycle as the Sanyo LIB. The only differences are the cutoff discharging voltage of 2.0 V and cutoff charging voltage of 3.6 V because of its relatively small capacity and voltage. Besides, two kinds of cells are placed in the PCM to discharge at a discharge rate of 1 C and 2 C.

Table 3. Design of charging and discharging experimental conditions.

Processing	Condition	Current (A)		Voltage (V)	
		Sanyo Battery	Sony Battery	Sanyo Battery	Sony Battery
Discharging shelving	Constant current 5 min	2.6 (1C), 5.2 (2C)	1 (1C), 2 (2C)	4.2	3.6
Charging shelving	Constant voltage and current 5 min	2.6 (1C)	1 (1C)	2.5	2.0

3. Results and Discussions

3.1. Temperature Change during LIB Cycle

When the LIB is charging and discharging, the reaction occurs inside the LIB, which produces heat and shows the increase of battery temperature. Figure 3 shows the temperature change during charging and discharging of Sanyo LIB under four different working conditions: extreme conditions, natural convection cooling, PCM cooling, and PCM combined with heat dissipation fins cooling at the ambient temperature of 25 °C. Figure 3a shows the temperature curve of LIB in two cycles. That can be seen from the figure, the temperature of LIB in the enclosed space rises from 30 °C to about 77.3 °C during discharging, which obviously exceeds the normal operating temperature of the battery. The high temperature has certain bad influence on the LIB. The long-term working under the extreme condition will cause the LIB internal electrolyte decomposition, the positive and negative electrode reaction,

and so on, which may cause the LIB thermal runaway and produce the safety risks. The highest temperature of the LIB is about 54.5 °C under PCM cooling, 66.2 °C under natural convection, 77.3 °C under extreme condition. Compared to the air cooling, the temperature of LIB using PCM cooling has a much smaller increase rate, and the highest temperature drops by 11.7 °C. Therefore, the results show that PCM can absorb some heat during the LIB discharging process, effectively reducing the LIB temperature. For the analysis of the cooling condition of the PCM with heat dissipation fins on the LIB, the heat dissipation fins have been adopted. The volume ratio of PCM and heat dissipation fins in the device is about 96%:4%. According to the diagram, the maximum temperature difference between the LIB in this working condition and PCM cooling condition is about 0.2 °C. The combination of heat dissipation fins can slightly reduce the temperature of LIB. The reason may be the fin structure cannot dissipate the latent heat in time due to its small volume ratio. In the research on the combination of PCM with heat dissipating fins, while giving full play to the maximum effect of heat dissipating fins, its cost and influence on the whole LIB structure should also be considered. Javani et al. [28] investigated heat transfer with PCMs in passive thermal management of electric and hybrid electric vehicles. Their results showed that the temperature distribution became about 10% more uniform when the PCM was applied in a 3 mm thickness around the LIB. The PCM with 12 mm thickness decreased the maximum temperature about 6.6 °C. In this research, the PCM not only has better cooling performance, but also makes the device having the advantages of small size and lightweight. In addition, the PCM in this study has a solid-solid phase change process, which avoids the liquid leakage. The device structure in this study is simpler and more practical, which may has a potential for commercialization.

Figure 3b shows the temperature change curve of LIB during six cycles. The temperature of LIB tends to be stable under various working conditions. However, the average of the maximum temperatures for the six cycles of LIB reaches about 77.8 °C in the enclosed space, which is in an unsafe state. It may cause great damage to the internal structure of the LIB and seriously affect the cycle service life of LIB. The PCM can have a good cooling effect on the temperature and make the average of the maximum temperatures for the six cycles of LIB keep at about 54.4 °C. The average of the maximum temperatures for the six cycles of LIB under the experimental condition of the combination of PCM and heat dissipating fins is about 54.3 °C, which is not significantly different compared to PCM cooling condition. The result shows that the effect of heat dissipation fins is not significant and the pure PCM cooling is the best choice due to the cost and complexity of the device structure. On the other hand, the LIB temperature rose at a slower rate and the temperature curve shifted slightly to the right as the cycle progressed. The heat generated inside LIB consisted of five parts: electrochemical reaction heat, ohmic internal resistance heat, polarization heat, electrolytic decomposition heat, and SEI decomposition heat. The electrolytic and SEI decomposition heat were very small and could be ignored when LIB was in the normal operating temperature range. The LIB would produce heat during the charging and discharging cycles. For discharging condition, the total chemical reaction was an exothermic reaction and the temperature rose theoretically, and for charging condition, the total chemical reaction was an endothermic reaction and the temperature drops theoretically. However, in the case of natural convection in Figure 3b, the temperature remains unchanged or even rises within a short period of time (region A) during the battery charging process. In the LIB charge process, although it is an endothermic process, the LIB generated heat such as ohmic internal resistance heat, polarization internal resistance heat, and electrochemical reaction heat more than itself heat dissipation, so that the temperature remains stable or even slightly rises.

(a) Change of charging and discharging temperature of Sanyo LIB

(b) The temperature changing of Sanyo LIB cycle

Figure 3. The temperature changing of LIBs during charging and discharging.

Figure 4 shows the temperature changes of LiFePO_4 battery in charging and discharging cycles under four different working conditions. It can be found that the highest temperature of the LIB under extreme conditions is about 40.6°C and the lowest temperature is about 35.1°C when the LIB is shelved after charging. The temperature of LiFePO_4 LIB will not be too high compared with Sanyo LIB when it works for a short time under extreme conditions due to its smaller LIB capacity, and lower internal polarization and ohmic resistance heat. The maximum temperature of Sony LIB is about 35.1°C under PCM cooling, 37.5°C under natural convection, 40.6°C under extreme condition. It is found that

the LIB temperature under PCM cooling decreases by 2.4 °C compared with the natural convection. In the case of the combination of PCM and heat dissipation fins, the temperature decreases 0.4 °C than PCM cooling due to the temperature of battery itself is low. In addition, the Sony LIB temperature in extreme conditions cannot be lowered to the level of other conditions during charging and shelving due to the heat is not dispersed in time. It can accelerate the degradation of the LIB and influence the LIB performance in extreme condition for a long time, which further prove the necessity of BTMS.

Figure 4. The temperature changes of LiFePO₄ battery during charging and discharging.

3.2. The Influence of Temperature on Battery Performance

Temperature is an important factor affecting battery performance parameters. Too high or low temperature will affect LIB capacity, charging and discharging efficiency, safety performance and result in battery performance degradation. Figure 5a shows the current change of the LIB in the charging and discharging cycle, and Figure 5b shows the voltage change. For the convenience of statistics, the x-coordinate in the figure represents the time step, and each step is 10 s. That can be seen from the figures, the current and voltage curves of the LIB have the same trend in each working condition. The current and voltage can reach the set rating in each charging and discharging cycle. However, as the cycles progresses, compared with the LIB under extreme conditions, the LIB curves in other conditions shift to the right, which is very similar to Figure 3b. The reason is related to the battery charging and discharging time. Under constant current conditions, the total flux of lithium ions should be roughly similar (both as diffusion in the electrolyte, and total flux into and out of the active material particles), and environmental conditions have little effect on it. However, at lower temperatures, a higher concentration gradient is required to overcome the slower diffusivity to meet the required flux. The higher concentration gradient leads to higher over potential and uneven utilization of electrodes. In turn, this leads to faster reaching of the cut-off voltage when working at lower temperatures. It can be clearly seen in Figure 5a that the LIBs in PCM and PCM-Fin cooling experiments seem to be faster reaching the cutoff voltage than the extreme condition and air cooling experiments in the first discharge cycle when all batteries start at the same state of charge (SOC). On the contrary, a higher temperature of LIB means that a constant current can be provided for a longer period of time. That can be seen in Figure 5b, the voltage drop of LIBs at higher temperature is smaller. In addition, according to Figure 3, it is found that in the constant current charging stage of the battery, the temperature of the battery decreased rapidly in the extreme condition and air cooling experiments, and the temperature is lower

than the other cases in a period of time due to the latent heat effect of PCM. It seems that the LIBs under PCM and PCM-Fin cooling conditions can be charged for a longer time in the later cycles than the other cases.

(a) Current curves

(b) Voltage curves

Figure 5. The current and voltage curves of Sanyo LIB.

Figure 6 shows the current and voltage changes in the LiFePO_4 battery during charging and discharging cycles. The current and voltage changes of LiFePO_4 LIB have the same trend under four different working conditions. Since the operating temperature of LiFePO_4 LIB under four working

conditions is around 30–40 °C, the LIB is in a normal working state and its current and voltage will not change much.

(a) Current curves

(b) Voltage curves

Figure 6. The current and voltage curves of Sony LIB.

Table 4 shows the capacity changes of Sanyo LIB charging and discharging cycles under different working conditions. It is found from the table that the LIB capacity has some changes in each working cycle. The average charging capacity of six cycles is 2414.6 mAh under the extreme conditions, 2399.4 mAh under natural convection, 2397.7 mAh under PCM cooling, and 2403.6 mAh under PCM combined with heat dissipation fins working condition. The average discharging capacity of six cycles

is 2412.7 mAh under the extreme conditions, 2398.3 mAh under natural convection, 2398.4 mAh under PCM cooling, and 2383.3 mAh under PCM combined with heat dissipation fins working condition. Table 5 shows the capacity changes of LiFePO₄ battery charging and discharging cycles under different working conditions. The average charging capacity of six cycles is 1022.6, 1034.9, 1031.6, and 1034.5 mAh, and the average discharging capacity is 1026.8, 1035.9, 1030.4, and 1032.1 mAh, under the extreme conditions, natural convection, PCM cooling, and PCM combined with heat dissipation fins working condition, respectively. The LIB capacity changes are related to the temperature. The battery capacity does not change significantly, which indicated that the LIB capacity is not significantly affected by short cycles even at high temperatures. Compared with the natural convection condition, the LIB discharging capacity under PCM cooling and PCM combined with heat dissipation fins decreased slightly. In the case of higher temperature, the battery reaches the cut-off voltage more slowly during the charging and discharging process, and the constant current charging and discharging time is longer, so the charging and discharging efficiency is higher, and the maximum capacity value is larger. However, the high temperature has a great influence on the capacity degradation rate of LIB [40]. The higher temperature leads to a quicker rate of various side reactions in the battery and faster the capacity degradation. Due to the low number of battery cycles in the experiments, the internal damage or possible side reactions that might have occurred at high temperatures had not yet become apparent. In the current application of LIB with the high efficiency and capacity, reducing the impact of itself side reaction and temperature are particularly critical, which is also a hurdle for the current LIB technology breakthrough.

Table 4. Capacity curve of Sanyo LIB in charge and discharge cycles.

Sanyo Battery Cycles	Excon		Air		PCM		PCM-fin	
	Charging Capacity (mAh)	Discharging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)
1	2416.836	2413.664	2397.757	2396.380	2396.886	2385.235	2399.645	2387.914
2	2415.543	2412.135	2398.268	2398.719	2401.686	2483.068	2404.635	2379.632
3	2414.601	2413.030	2401.894	2400.978	2402.126	2379.272	2405.866	2384.824
4	2413.782	2412.072	2395.317	2399.563	2396.722	2382.227	2405.228	2386.124
5	2414.819	2413.401	2401.893	2396.380	2395.279	2384.336	2403.516	2378.967
6	2412.173	2411.815	2400.974	2397.655	2393.280	2376.504	2402.460	2382.489

Table 5. Capacity curve of LiFePO₄ LIB in charge and discharge cycles.

Sony Battery Cycles	Excon		Air		PCM		PCM-fin	
	Charging Capacity (mAh)	Discharging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)	Charging Capacity (mAh)
1	1031.890	1032.637	1035.779	1033.977	1032.103	1031.853	1035.741	1024.440
2	1008.673	1018.444	1033.233	1035.806	1032.359	1028.684	1031.933	1033.147
3	1018.732	1023.337	1034.633	1036.101	1030.632	1029.485	1034.568	1033.514
4	1022.702	1026.527	1035.109	1036.212	1031.216	1030.508	1035.078	1033.570
5	1025.826	1028.784	1035.155	1036.361	1031.566	1030.718	1034.831	1033.665
6	1028.002	1030.793	1035.320	1036.645	1031.840	1031.291	1035.110	1034.102

3.3. The PCM Influence on LIB Temperature under Different Discharging Ratios

Figure 7 shows the temperature curves of Sanyo and Sony LIB under the conditions of natural convection and PCM cooling. It is found that the PCM has a good effect to decrease the LIB temperature no matter it is discharged at a rate of 1 C or 2 C. Compared with natural convection cooling, the highest temperature of Sanyo LIB decreases about 4.7 °C and 12.8 °C for 1 C and 2 C discharging, respectively, and the highest temperature of Sony LIB decreases about 1.1 °C and 2 °C. The temperature reduction

effect of PCM on high rate discharge LIB is more obvious. In the charging and discharging cycles, Sanyo LIB generates more heat due to its large capacity, and PCM absorbs more latent heat. The PCM has the most obvious effect on the Sanyo battery in a 2 C discharging rate among all experiments.

(a) The temperature curves of Sanyo LIB

(b) The temperature curves of Sony LIB

Figure 7. The temperature curves of Sanyo and Sony LIB under 1 C, 2 C discharging.

4. Conclusions

PCM has been widely used in the thermal management of LIB due to its advantages. In this paper, the changes of LIB temperature and capacity under different working conditions and discharge

ratios are analyzed in order to further analyze the PCM influence of LIB thermal management and design an effective BTMS. The conclusions are as follows:

(1) The LIB temperature rises during the discharge process, and the PCM can effectively reduce the LIB temperature and keep its capacity stable. The average highest temperature of Sanyo LIB under the PCM cooling is about 54.4 °C in the 2 C discharge rate especially, and it is about 12.3 °C decrease compared with the natural convection cooling.

(2) The heat dissipation fins can reduce the LIB temperature, but the current effect is not very significant. Further optimization of the combination with heat dissipation fins and PCM is also an important direction in the thermal management of LIB.

(3) The LIB capacity changes are related to the temperature. In the discharge rate cycles, the LIB temperature of PCM cooling and PCM combined with heat dissipation fins decreased slightly, and the capacity decreases compared with the natural convection condition. The battery temperature and capacity increase slightly under extreme conditions.

(4) The PCM have a bigger temperature impact on Sanyo LIB. Sanyo LIB generates more heat due to its large capacity, and PCM absorbs more latent heat. The temperature reduction effect of PCM on high rate discharge LIB is more obvious.

In the future study, PCM combined with other cooling way efficiently and developing the PCM of higher latent heat, better heat conduction performance will be an important direction of battery BTMS.

Author Contributions: Conceptualization, M.C., S.Z., and J.W. (Jingwen Weng); Methodology, M.C., D.O. and J.W. (Jian Wang); Investigation, L.Z., S.Z., and G.W.; Writing-Review & Editing, M.C., S.Z., and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2018YFC0808600), the Open Project of State Key Laboratory of Fire Science (HZ2020-KF08), Natural Science Foundation of the Higher Education Institutions of Jiangsu Province (19KJB620003), and the Double Innovation Plan of Jiangsu province.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Air	Air cooling
BTMS	Battery thermal management system
Excon	Extreme condition
LiFePO ₄	Lithium iron phosphate
LIB	Lithium-ion battery
PCM	Phase change material
PCM-fin	PCM with heat dissipation fins
SOC	State of charge

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