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Experimental investigation of battery thermal management system for electric vehicle based on paraffin/copper foam

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ABSTRACT

To enhance the heat transfer of phase change material in battery thermal management system for electric vehicle, a battery thermal management system by using paraffin/copper foam was designed and experimentally investigated in this paper. The thermal performances of the system such as temperature reduction and distribution are discussed in detail. The results showed that the local temperature difference in both a single cell and battery module were increased with the increase of discharge current, and obvious fluctuations of local temperature difference can be observed when the electric vehicle is in road operating state. When the battery is discharging at constant current, the maximum temperature and local temperature difference of the battery module with paraffin/copper foam was lower than 45 °C and 5 °C, respectively. After the battery thermal management system was assembled in electric vehicle, the maximum temperature and local temperature difference in road operating state was lower than 40 °C and 3 °C, respectively. The experimental results demonstrated that paraffin/copper foam coupled battery thermal management presented an excellent cooling performance.

1. Introduction

It is well known that the overall performance of electric vehicle (EV) is restricted by the power battery. Both excessive high and low operating temperatures will affect the performance especially the cycle life of battery [1]. The battery operating at excessive high temperature may lead to safety risks such as overheating, combustion and even explosion, and at a temperature well below ambient, cold startup is inevitable to be solved [2,3]. Therefore, in order to improve the thermal performance and reduce the maintenance cost of EVs, and then promote energy conservation and emission reduction of the whole society, the efficient and feasible battery thermal management (BTM) system is essential [4,5].

In recent years, the BTM system based on phase change material (PCM) have received more and more attention by the reason of zero extra power consumption of battery. After Al-Hallaj and Selman [6] first demonstrated the PCM-based BTM system, the effective and economy of PCM used for BTM system were confirmed sequentially. Design, simulation and experimental validation of lithium-ion battery thermal management with PCM for an electric scooter have been reported in succession [7,8]. Mills and Al-Hallaj [9] presented the simulation of PCM-based BTM system for laptop. Al-Hallaj et al. [10–12] also showed the temperature rise and distribution of air-cooled vs. PCM-cooled, as well as at high current and ambient temperature by simulation method. Alrashdan et al. [13] even studied the thermo-mechanical behaviors of the PCM which used in BTM system. In the above works, all the PCM used in BTM system is paraffin due to its advantages such as low cost and reasonable phase change temperature. However, a common disadvantage of paraffin is low thermal conductivity. To enhance the heat transfer of paraffin, various materials with high thermal conductivity such as carbon nanofiber [14], carbon nanotube [15], expanded graphite [16–18], graphene [19] and metal foams [20] was added to form composite PCM. The power materials in the paraffin may sink after repeated melting-solidification process and then increase the local temperature difference of battery module, while the metal foams would not. Zhang et al. [21] have designed a BTM system based on paraffin/copper foam. According to their

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designed BTM system, we have presented the temperature rise of the battery module when the battery is discharging at constant discharge rate [22]. However, the BTM system is not studied under actual EV operation state, that is, the fluctuations of discharge current and the initial environment temperature are ignored.

Taking into account both the maximum temperature and local temperature difference are equally important for battery within EV, based on our previous work, the temperature reduction and distribution of the BTM system by using paraffin/copper foam are experimentally investigated in the present study. The thermal performances of the BTM system under actual EV operation state are discussed in detail.

2. Experimental setup

Fig. 1 shows the schematic diagram of the BTM system based on paraffin/copper foam. In the experiment, the cylindrical 42110-size (42 mm in diameter and 110 mm in height) $LiFePO_4$ battery with normal capacity 10 Ah was used as battery cell. A battery module contains 24 cells and the cells are combined with a cross arrangement as positive terminal-negative terminal-positive terminal to avert large local temperature difference especially at the middle location. The voltage and capacity of each battery module (12 S × 2 P: S, series; P, parallel) was 38 V and 20 Ah, respectively. The paraffin/copper foam composite PCM were filled in the space between different cells. The melting point of base material paraffin is 37 °C, and the latent heat of paraffin is 180 $kJ\ kg^{-1}\ K^{-1}$, the thermal conductivity, 0.2 $W\ m^{-1}\ K^{-1}$. The framework material copper foam was bought from Changsha Liyuan New Material Co., Ltd. China and its main parameter was depicted as follows: PPI (pore per inch) was about 20, density was about 0.4 $g\ cm^{-3}$. At first, the single battery cell and battery module were charged and discharged with NEWARE Battery Testing System. The Agilent Data Acquisition Instrument (34970A) with K-type thermocouple was used to collect temperature data. When the BTM system was assembled in EV, an uninterrupted power supply (UPS) was used to supply power for computer and Agilent Data Acquisition Instrument. The UPS was supplied by Shante electronic instrument Co., Ltd. China. The experiment of the EV in road operating state was performed on “West Zhonghuan Road-No. 5 Central Road-West Waihuan Road-No. 3 South Road” in Guangzhou Higher Education Mega Center with a maximum speed of 65 $km\ h^{-1}$.

3. Results and discussion

Fig. 2 shows the temperature response of single battery cell without BTM system at difference discharge rate. The temperatures at three representative locations (positive terminal, negative terminal and the middle) of the battery cell were acquired. It is obvious that the discharge time increases with the increase of discharge rate and the stability of discharge platform decreased. When the battery cell is discharging at 3 C, the maximum temperature of the battery reached to 65.10 °C. When the discharge rate increased to 5 C, the maximum temperature of the battery was up to 89.79 °C, and the discharge time is 620 s, during which time the maximum temperature of the battery is higher than 50 °C. The temperature difference of positive and negative terminals during the discharge process are also obvious and the maximum value was over 12 °C. According to the temperature response of positive terminal, middle part and negative terminal, the temperature of positive terminal was higher than other locations due to its more drastic chemical reaction. Overall, the heat generation rate and amount of the power battery increased with charge and discharge current. As the difference of chemical reaction at positive and negative terminals of the battery cell is different, the local temperature difference is changing during the whole discharge process. For the battery module, the local temperature difference between different cells may be more evident especially after the battery repeated used.

After the battery module was assembled in EV, the EV started at low speed and accelerated gradually, the temperature response of the battery module without BTM system when the EV was running is shown in Fig. 3. Where, T_1 to T_4 represent the temperature of negative terminal (low temperature) of the battery and T_5 to T_6 represent the temperature of the positive terminal (high temperature), and ΔT stands for the maximum local temperature difference. As the EV speed changed with the road condition, the temperature of different battery cells in the module and the maximum local temperature difference all presented obvious fluctuations. When the speed of EV was 50–60 $km\ h^{-1}$, the tested discharge rate of battery module was about 3–3.5 C. When the travel time reached to 1745 s, the maximum temperature of the battery module exceeded 50 °C. As the heat in the center of the battery module could not be transported out as soon as possible, the local

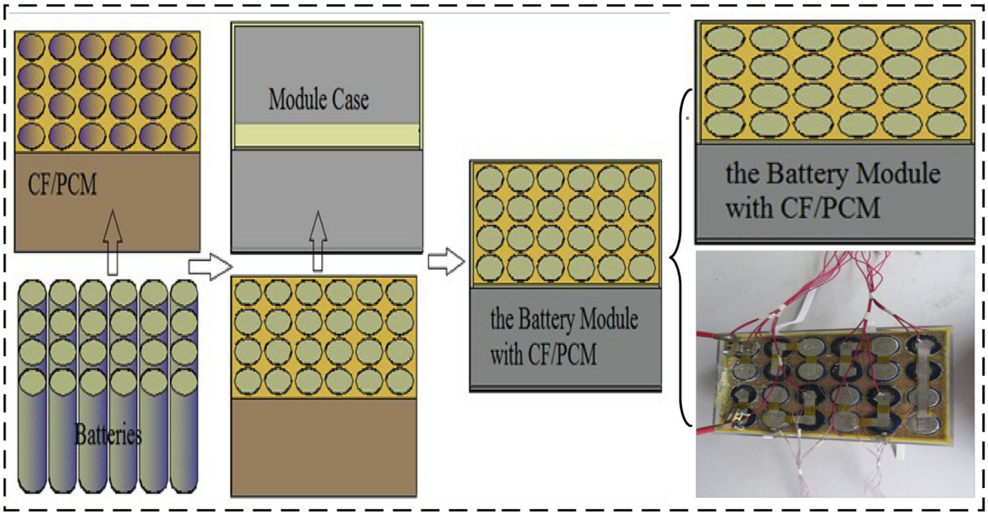

Fig. 1. Battery thermal management system based on paraffin/copper foam.