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Experimental research on the effective heating strategies for a phase change material based power battery module

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A B S T R A C T

Constructing a complete battery thermal management (BTM) system consisting of both the heating and cooling functionalities is critical to guarantee the cycling life and safety of the power battery pack. In this work, we focus on the neglected issue of replenishing a cooling system with a heating functionality in a standardized power battery module. Two kinds of heating strategies, including forced air convection (FAC) heating and silicone plate (SP) heating are developed and then optimized on an advanced phase change material (PCM)-cooling based battery module. The experimental results show that the performance of the FAC heating strategies can be optimized by constructing a "close-ended" battery pack and increasing the fan number to recycle the waste heat and uniform the air flow field, respectively. The strategy of SP heating at 90 W demonstrates the most effective heating performance. For instance, an acceptable heating time of 632 s and a second lowest temperature difference of 3.55 °C can be obtained, resulting in a highest comprehensive evaluation factor of 0.42, much higher than those of other heating strategies (0.29–0.32). These encouraging results may raise concerns about constructing suitable cooling and heating functionalities simultaneously in a BTM system to realize a target oriented use, particularly those targeting various harsh operating environments.

1. Introduction

Under the concerns about the environment deterioration and rapid consumption of the fossil fuels, the development of clean energy has become a major strategy for most countries. Hence, the electric vehicles or hybrid electric vehicles (EVs/HEVs) are now the widely accepted replacements of the traditional vehicles with internal combustion engines due to their environment friendliness and high energy efficiency [1–3]. As the energy storage system of EVs/HEVs, lithium-ion batteries (LIBs) have shown great advantages on their high power density and durability compared to other secondary batteries [4–6]. However, considering the basic requirements from EVs/HEVs to the power batteries, including high-rate discharge capability [7–10], long discharge time [11,12] and long cycle life [13–15], the stability of the power batteries under harsh working environment, e.g., long-time operating, various road and temperature conditions, is one of the most important factors that restrict the development of the EVs/HEVs, especially the thermal stability.

In general, the thermal stability mainly consists of two aspects: the heat dissipation and temperature uniform capability under high temperature [16–18], as well as the heating and thermal insulation capability under low temperature [19–21]. In details, the working temperature and temperature difference (ΔT) of the battery module should be maintained below 50 and 5 °C [22], respectively, without which sharp degradation of the capacity or even safety problems may occur [23–26]. On the other hand, under the severely cold environment, the battery module should be heated to 10 °C at least to guarantee the normal operating and cycling life of the cells [27,28]. Thus, a complete battery thermal management (BTM) system must possess both heating and cooling functionalities.

The past decades have witnessed the significant progress of the design and optimization of the single heat dissipation systems [29–32], whereas a few works have been devoted to the heating functionality. The only relevant reports are basically focusing on heating a single cell or constructing a single heating method for a facile and non-standardized battery module without a cooling system [27,33–35]. For example, Zhang et al. [36] demonstrated a single heating system using metallic resistance heating, and it presented higher heating efficiency and thermo-consistency than the Positive Temperature Coefficient heating method. Zhu et al. [37] reported a single heating method for large laminated power LIBs using the Alternating Current (AC) pulse heating. However, the neglected issue of replenishing the cooling system with a

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Nomenclature

BTM	battery thermal management
FAC	focused air convection
FAC-O	FAC heating strategy with “open-ended” design
FAC-C	FAC heating strategy with “close-ended” design
SP	silicone plate
PCM	phase change materials
ΔT	temperature difference (°C)
EVs	electric vehicles
HEVs	hybrid electric vehicles
LIBs	lithium-ion batteries
AC	alternating current
T_{ave}	average temperature of the batteries (°C)
γ	heating efficiency factor
δ	temperature deviation index
β	required heating time index
C_p	heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
P	heating power (W)
t_{10}	required heating time for the T_{ave} to obtain 10 °C
η_δ	temperature difference factor
η_β	heating time factor
η	comprehensive evaluation factor
PTC	positive temperature coefficient
MRF	metallic resistance heating

heating functionality [38,39], especially for the standardized battery module, becomes a major barrier of developing advanced battery systems for the promotion of EVs/HEVs. The main reason could be ascribed to the complication of taking both the cooling and heating functionalities into account and the threshold of constructing a commercially standardized battery module.

In the present work, two kinds of heating strategies have been developed on a phase change material (PCM)-cooling based battery module, i.e., forced air convection (FAC) heating and silicone-plates (SP) heating. According to the minimum operating temperature of 10 °C and the widely accepted maximum ΔT of 5 °C for guaranteeing the cycling life and safety of the battery module, a QUALIFIED heating performance of different strategies is defined qualitatively as follows: (1) the average temperature (T_{ave}) of the battery module should be heated to 10 °C within 15 min; (2) the ΔT of the whole battery module should be maintained below 5 °C. By optimizing and comparing the heating performance of them, it is concluded that in the FAC strategy, the “close-ended” design of the battery pack and the increase of the fan number are beneficial to recycling the waste heat and uniforming the air flow field in comparison to the “open-ended” design, respectively. Among various heating strategies, the SP heating reveals much more excellent performance on the heating time and temperature gradient.

2. Experimental

2.1. Construction of the FAC heating strategies for the battery module

Fig. 1 shows the structure design of the FAC heating strategy for a standardized PCM-cooling -based battery module derived from our previous work [40]. In brief, 12 holes with a diameter of 18.5 mm were drilled on the paraffin/expanded graphite/low-density polyethylene based PCM plates, in which 24 commercial 18650 power LIBs with a capacity of 2 A h were placed (Dongguan Shineng Electronic Technology Co., Ltd.) (Fig. 1a). Detail parameters of the batteries are shown in Table S1. The thermal conductivity, phase change temperature and latent heat of the PCM plate are 1.38 $\mathrm{W\,m^{-1}\,K^{-1}}$, 44 °C and 87.4 $\mathrm{J\,g^{-1}\,K^{-1}}$, respectively. 24T-type thermocouples (TC-TFF 2 × 0.25 × 1000 mm, accuracy ± 0.1 °C, USA) were mounted on the surface center of each battery. The batteries were connected in 6S × 4P configuration (six batteries in series and four strings in parallel), forming a standardized battery module with a rated voltage and capacity of 21.6 V and 8 A h, respectively. In order to construct a PCM cooling system approaching to practical application, four aluminum fins with specifications of 110 × 121 × 9 mm (Shenzhen Runrong hardware products Co., Ltd) were coupled on the outer surface of the PCM module to enhance the surface heat transfer capability [41]. Besides, the box housing of the battery module was constructed by several acrylic plates (Shenzhen Tianya Plastic Products Co., Ltd.). As illustrated in Fig. 1b and 1e, three rows of Ni-Cr alloy heating wires (Shanghai Fengshan alloy materials Co., Ltd.) were placed in the battery pack. Three fans (60 × 60 × 25 mm, 110–240 V-EC, 50/60 Hz, 5 W Shanghai GuoHeng Motor Co., Ltd.) and three corresponding outlets (60 × 60 mm) were installed on the two opposite surfaces of the battery pack. Their flow rate and pressure drop were tested and presented in Table S2. In addition, an optimized “close-ended” battery pack was also constructed by adding a canvas connection tube (Hebei Beite Machine tool Accessories Manufacturing Co., Ltd.) to recycle the waste heat of the flowing air (Fig. 1c and d). Fig. 1d displays the experimental setup of the FAC heating strategy with the “close-ended” design. The battery pack was heated with various heating power of 120, 180 and 220 W and various operating fan numbers from 1 to 3 for 15 min. The resultant “open-ended” and “close-ended” FAC (FAC-O and FAC-C) heating strategies were denoted as FAC-O-*x*W-*y*F and FAC-C-*x*W-*y*F, respectively, where *x* and *y* represented the heating power and the number of the operating fans, respectively.

2.2. Construction of the SP heating strategies for the battery module

Fig. 2 shows the structure design of the SP heating strategy. Two silicone heating plates with a size of 300 × 120 × 2 mm (Shenzhen Cothion Silicone Rubber Products Co., Ltd.) were fixed on both sides of the PCM surface, and the power source (YK-CD3050) was purchased from Yucoo Network Equipment Co., Ltd. The heat flux will transfer through the solid state PCM and immediate heat the batteries. Like the FAC heating strategies, four aluminum fins were coupled on the outer surface of the module to simulate an actual PCM cooling system. The battery pack was heated with various heating power of 32, 72 and 90 W for 15 min. The resultant SP heating strategies were denoted as SP-*x*W, where *x* represented the heating power.

2.3. Definition of the evaluation factors for the heating performance

In order to evaluate the heating performance under different heating strategies, we defined the heating efficiency factor of γ, temperature deviation index of δ and required heating time index of β as follows:

$$\gamma = \frac{m_{battery} C_p T}{Pt} \tag{1}$$

$$\delta = \frac{\Delta T}{5} \tag{2}$$