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Experimental study on a novel battery thermal management technology based on low density polyethylene-enhanced composite phase change materials coupled with low fins

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HIGHLIGHTS

- Low density polyethylene (LDPE)-enhanced composite PCM (L-CPCM) is prepared.
- Introducing LDPE as a third component improves the mechanical properties greatly.
- LDPE framework fixes the melted PCM, preventing PCM leakage to a great extent.
- L-CPCM technology shows much better cooling effect compared to nature air cooling.
- Coupling L-CPCM with fins enhances the heat transfer capability from L-CPCM to air.

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ABSTRACT

Phase change materials (PCM) cooling has been considered as the most potential alternative to traditional battery thermal management (BTM) technology, but significant challenges remain: PCM leakage, poor mechanical properties and low surface heat transfer capability between PCM and the external environment. Here, we develop a BTM technology based on the ternary composite materials of expanded graphite (EG), paraffin (PA) and low-density polyethylene (LDPE) coupled with low fins. The as-doped LDPE framework can not only enhance the mechanical molding property but also prevent PA leakage to a great extent. Coupling with low fins endows the entire BTM system with high surface heat transfer capability. For instance, the as-prepared LDPE/EG/PA composite PCM shows much better mechanical properties and cooling effect in comparison to EG/PA composite and air cooling, respectively. After coupling with low fins, the as-constructed PCM-based battery module presents excellent heat dissipation performance, keeping the battery pack working under the safety temperature of 50 °C and temperature difference of 5 °C for lithium-ion power batteries, even at an extremely high discharge rate of 3.5 C.

1. Introduction

Nowadays, energy and environment are two important concerned issues for human beings. Concern centers around the depletion of resources and pollutants such as carbon emissions, restricting an unlimited use of conventional resources of petroleum and natural gas. Therefore, the electric vehicle has been considered as the most potential alternative for traditional vehicles because of its green energy power, primarily constructed by lithium-ion power battery (LIB). However, effective thermal management of LIB module has always been an essential issue according to the best working temperature range of 25–50 °C and temperature difference below 5 °C in a LIB module [1–4].

A variety of thermal management techniques and designs have been widely investigated in the literature, including air cooling (natural or forced air convection) [5–9], liquid cooling [10–14], heat pipe cooling [15–17] and phase change materials (PCM) cooling system [18–22]. Natural air cooling technology is suffering from low cooling efficiency, which failed to meet the requirement for the increasing power output of the electrical vehicle [23]. Thus, exploring cooling technology with enhanced heat dissipation performance has been a long-pursued goal for the development of a state-of-the-art battery thermal management (BTM) system. Wang et al. [24] reported that an improved temperature range of LIB module could be achieved by forced air cooling. Jin et al. [25]

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Nomenclature

PCM	phase change material
BTM	battery thermal management
LIB	lithium-ion battery
PA	paraffin
EG	expanded graphite
LDPE	low-density polyethylene
L-CPCM	composite PCM with LDPE
CPCM	composite PCM without LDPE
L-CPCM-F	L-CPCM coupled with fins
C	discharge rate
$R_{\text{CP-air}}$	thermal resistance from the PCM center to air [$\text{m}^2\,\text{K}\,\text{W}^{-1}$]
R_{PCM}	thermal conduction resistance of L-CPCM [$\text{m}^2\,\text{K}\,\text{W}^{-1}$]
$R_{\text{P-air}}$	heat transfer resistance from the PCM surface to air [$\text{m}^2\,\text{K}\,\text{W}^{-1}$]

T_{CP}	L-CPCM center temperature [°C]
$T_{\text{S-PCM}}$	L-CPCM surface temperature [°C]
T_{air}	air temperature [°C]
Q	power [W]
ΔT	temperature difference [°C]
$\Delta T_{\max}$	maximum temperature difference [°C]
T_t	terminated surface temperature [°C]
h	hour [h]
h	heat transfer coefficient [$\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$]
k	thermal conductivity [$\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$]
δ	characteristic dimension
D	discharge
R	rest
C	charge

developed a novel liquid cold plate for thermal management of electric vehicle battery, and the results showed that the oblique structure significantly improved the cooling performance of the liquid cold plate. Zhao et al. [17] found that a heat pipe thermal management system could maintain the temperature of LIB pack in an appropriate temperature range. Despite the fact that forced air cooling, liquid cooling and heat pipe cooling systems in a battery module present effective performance of temperature control and uniformity, the design of the structure in the system is relatively complex [8,9], especially for liquid cooling due to the risk of refrigerant leakage [10,12]. Moreover, additional components of active energy supply such as pumps and fans, which increase energy consumption, are required for air cooling and liquid cooling [26,27]. Thus, passive cooling technology represented by PCM cooling has been considered as the most potential alternative of the above traditional BTM system [28–32]. During the melting/solidifying process, PCM can absorb/release abundant latent heat, leading to a relatively constant temperature of the battery system. PCM-based passive thermal management technology was first proposed by Al-Hallaj and Selman [33]. It showed a much better cooling performance than conventional BTM systems, especially for large-scale batteries and/or under harsh working conditions. Rao et al. [34] concluded that PCM with proper thermal properties were necessary for a well-designed passive BTM system by numerical simulation study. Wang et al. [35] investigated a BTM system using composite PCM of paraffin (PA)/aluminum foam for LIB, and the results demonstrated that it presented an ideal cooling effect for controlling the temperature rise of LIB during discharge.

Nevertheless, in practical applications, closed tanks or containers are necessary to prevent leakage of traditional PCM, giving rise to a relatively complex structure. Inhomogeneity of multiple components or even module crack of composite PCM such as paraffin (PA)/expanded graphite (EG) module happens during the mechanical molding and/or repeated melting/solidifying process [36,37]. On the other hand, single PCM-based cooling technology usually presents low surface heat transfer coefficient between PCM and air. Thus, thermal energy stored by PCM cannot be transferred to the external air environment effectively, resulting in a decreasing cooling effect during long-term/harsh working cycles [38].

Therefore, to address the above issues, a novel BTM technology was developed based on the ternary composite materials of EG, PA and low-density polyethylene (LDPE) coupled with low fins. As highlighted here, in contrast to conventional composite PCM, the as-prepared LDPE-enhanced composite PCM demonstrated not only superior mechanical properties for machining and long-term/harsh working cycles, but also much better anti-leakage performance. Furthermore, for the first time, low fins are used to couple with PCM cooling technology for endowing the whole BTM system with high surface heat transfer capability, thereby enhancing the heat dissipation performance of the entire module.

2. Materials preparation

Composite PCM was prepared through a physical mixing method. First, industrial-grade PA (melting point of 44 °C) was melted at 60 °C in an oil bath for 0.5 h using a low-speed mixer (DC-1-100W, Changzhou Wanhe instrument manufacture Co., Ltd.). Secondly, EG (obtained by heating the expandable graphite (average particle size: 150 μm, expansion ratio: 220 mL g^{-1}) at 760 °C for 180 s in a muffle furnace) with an EG/PA mass ratio of 1:9 was added to the melted PA slowly with continuous stirring to absorb PA and enhance the thermal conductivity of the materials. Finally, a predetermined amount of LDPE (Sinopec Shanghai Petrochemical Co., Ltd.) was added to the mixture and the temperature of the oil bath was increased to 135 °C for 2 h. The mass ratio of EG/PA composite and LDPE was 7:3. After that, the as-obtained mixture was gradually cooled to room temperature. The as-obtained LDPE/EG/PA composite PCM was denoted as L-CPCM. For comparison, another composite PCM without LDPE was prepared through the same process with an EG and PA mass ratio of 1:9, and denoted as CPCM.

3. Experimental setup

3.1. Design of the battery module with L-CPCM

Fig. 1a shows the schematic diagram of the experimental system. 12 holes with diameter of 18.5 mm were drilled on L-CPCM, in which 24 commercial 18,650 Li-ion power batteries with capacities of 2 A h were placed (Fig. 1b). All of the cells were connected in 6S × 4P configuration (six cells in series and four strings in parallel). The batteries were produced by Dongguan Shineng Electronic Technology Co., Ltd. Detail parameters of the battery pack used in this study are listed in Table 1. In order to optimize the surface heat transfer capability between air and L-CPCM, we designed a BTM system coupling the as-prepared L-CPCM-based battery pack with heat dissipation fins (Fig. 1c). The BTM system consisted of four aluminum fins and a battery pack with L-CPCM in the pattern of compact sandwich structure. The size of the basic aluminum fin was 110 × 121 mm^2, and the fins measured 1.2 mm in width by 9 mm in height.