



# An experimental study of thermal management system using copper mesh-enhanced composite phase change materials for power battery pack



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## ABSTRACT

As an important method for battery thermal management, traditional phase change material (PCM) technology is facing challenges due to the relatively low thermal conductivity, weak skeleton strength and/or leakage phenomenon of PCM. Herein we develop a copper mesh (CM)-enhanced paraffin (PA)/expanded graphite (EG) composite as a composite PCM for battery thermal management. EG with porous structure can absorb liquid phase PA, preventing PA leakage. CM acts as a skeleton to further enhance both the thermal conductivity and strength of the whole module. As a result, the as-constructed CM enhanced PCM of PA/EG plate (PCMP) presents much better heat dissipation performance and temperature uniformity compared to PCMP without CM, especially in harsh working conditions. Moreover, with forced air convection, copper fins exposed from the composite may play a crucial role in not only heat dissipation, but also disturbing the air flow, and thus further strengthen the heat transfer capability.

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## 1. Introduction

Pure/hybrid electric vehicles (EVs/HEVs) are more environmentally friendly than conventional vehicles because of their green energy power [1]. As one of the key components in EVs/HEVs, power battery pack is restricted by its safety issue, especially that arisen from the high temperature and/or non-uniform temperature distribution. It is well known that the temperature of all cells must be strictly maintained below the safety temperature of 65 °C [2,3] as well as the maximum temperature difference is not allowed to exceed 5 °C across the entire pack [4–6]. However, cells in the power battery pack are vulnerable to overheating from rapid discharging, overcharging and/or excessive ambient heating, which may also result in non-uniform temperature distribution of the entire power battery pack. Such overheating and non-uniform temperature distribution can lead to rapid cell degradation and thereby shorten the battery life [7]. In extreme cases, catastrophic destruction, such as fire and explosion, occurs as heat accumulates uncontrollably, namely, thermal runaway [8].

Therefore, battery thermal management (BTM), including traditional heat dissipation methods, such as air-based [9–11], liquid-based [12–14] and heat pipe-based cooling [15–17] has been considered essential for the power batteries of EVs/HEVs. Air cooling system is now suffering from the low cooling efficiency, which couldn't meet the demands for the increasing power output of EVs/HEVs. Such shortcomings can be overcome by using liquid-based [18] and heat pipe-based system with high cooling efficiency. However, they require extra energy supply components and/or complicate the structure of the battery system [19]. Recently, a kind of simple thermal management system based on phase change material (PCM) has been considered as an alternative to the aforementioned traditional system. PCM can absorb/release abundant latent heat during the melting/solidifying process, giving rise to a relatively constant temperature of the battery system. A passive thermal management solution using PCM as heat dissipation source was first proposed by Al-Hallaj and Selman [20]. The as-constructed simple BTM system consisted of only PCMs filling in the gap between batteries. It showed a much better performance on heat dissipation than conventional BTM system, especially for large-scaled batteries and/or under harsh working conditions. Rao et al. [21] reviewed the details of various thermal management methods and concluded that PCM with proper thermal properties

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## Nomenclature

T	Temperature (°C)
$\Delta T$	Temperature difference (°C)

### Subscripts

m	Melting
x	Cell number
max	Maximum

### Acronyms

PCM	Phase change material
PA	Paraffin
EG	Expanded graphite
EVs	Pure electric vehicles
HEVs	Hybrid electric vehicles
BTM	Battery thermal management
MF	Metal foam
CM	Copper mesh
PCMP	Phase change material plate
ANC	Air natural convection

is very promising for use in BTM systems.

Paraffin (PA) is currently the most widely used PCM for BTM because of its high latent heat, low cost and suitable phase-change temperature [22,23]. Unfortunately, one of the most important bottlenecks that limit the applications of PA is its poor thermal conductivity. Thus, many different approaches have been developed to enhance the thermal conductivity of PA by adding a second component such as carbon fiber [24], metal foam (MF) and expanded graphite (EG) [25–31]. A sandwiched cooling structure using copper MF saturated with PA was designed by W.Q. Li et al. [2]. The as-prepared composite presented a much better cooling effect compared to pure PA. Angelo Greco et al. [32] developed a simplified one dimensional model to investigate the thermal management of a cylindrical battery cell based on PCM/compressed expanded natural graphite. The graphite-matrix bulk density was identified as an important parameter for such a cooling strategy. Then a coupled thermal and electrochemistry model was performed for investigating the PCM/compressed expanded natural graphite passive cooling technology for both cylindrical battery cell and battery module scale [33]. From a battery pack point of view, Hassan Fathabadi [34] prepared PA/EG composites for a simulative BTM system, and the result showed that the temperature rise could be slowed down by doping EG and the temperature uniformity could be improved by increasing the EG mass content. Nevertheless, this kind of binary PCM composites still exhibits obvious limitations: (1) For PA/MF composites, the shape of the material is hard to tailor, and leakage of liquid-phase PA occurs, leading to a decreasing heat storage or even safety problems; (2) PA/EG composites still present relatively low thermal conductivity and skeleton strength, resulting in lower cooling effect in comparison to metal-enhanced PCM and module crack during the repeated melting/solidifying process, respectively.

To address these problems, we report herein the fabrication of a ternary PA/EG/copper mesh (CM) PCM plate (PCMP), and then use it for BTM. As highlighted here, EG with porous characteristic can absorb liquid phase PA, preventing PA leakage. CM acts as a thermal conductivity skeleton to further increase the thermal conductivity of the whole PCM module, and also enhance the skeleton strength. Moreover, copper fins exposed from the composite play an

important role in not only heat dissipation, but disturbing the air flow, forming abundant turbulence, and thus further strengthen heat transfer capability.

## 2. Materials preparation and characterization

### 2.1. Preparation and characterization of composite PCMs

Industrial grade PA (melting point  $T_m = 42^\circ\text{C}$ ) was used without further treatment. Expandable graphite (average particle size:  $150\ \mu\text{m}$ , expansion ratio:  $220\ \text{ml g}^{-1}$ ) was obtained from Qingdao Bai Xing Graphite Co., Ltd.

EG was obtained by heating the expandable graphite at  $800^\circ\text{C}$  for 60 s in a muffle furnace. PA was heated to  $80^\circ\text{C}$ . After complete melting, the liquid PA was mixed with EG at a mass ratio of 4:1 under mechanical agitation. The as-prepared PA/EG composite was put in a mold for hot-compaction. Subsequently, a milling machine was used to fabricate a board-shaped composite PCM with an overall dimension of  $70 \times 90 \times 5\ \text{mm}^3$ .

The microstructure of the composite PCMs was observed using a Scanning Electron Microscope (SEM, Hitachi S-3400 N, Japan). Two  $10 \times 10 \times 1\ \text{mm}^3$  plate samples were used to measure the thermal conductivity with a LFA447 NanoFlash™ system (range:  $0.1\text{--}2000\ \text{W m}^{-1}\text{k}^{-1}$ , accuracy:  $\pm 5\%$ , repeatability:  $\pm 3\%$ ). The melting point and latent heat of composite PCMs and pure PA were measured using a Differential Scanning Calorimeter (DSC2910, Texas Instrument Inc, USA) under  $\text{N}_2$  atmosphere with a heating rate of  $5^\circ\text{C min}^{-1}$ .

### 2.2. Preparation of composite PCMP and CM-enhanced PCMP

CM with a thickness of 0.5 mm was used as the third component. Fig. 1(a) shows the fabrication scheme of the CM-enhanced PCMP (CM-PCMP). A section of  $80 \times 90\ \text{mm}^2$  was cut from the CM material and sandwiched between two PA/EG composites, leaving only an area of  $5 \times 90\ \text{mm}^2$  exposed on both sides. A hot-compaction process was then carried out to fabricate CM-PCMP. The side view and magnification at the cross section of CM-PCMP indicate that CM can be completely imbedded in the composite PCMP (Fig. 1(b)). For comparison, another PA/EG composite plate (denoted as PCMP) was also prepared through the above same procedure without adding CM during the hot-compaction step.

## 3. Experimental setup

### 3.1. Design of experimental system

A schematic diagram of the experimental system is shown in Fig. 2(a). A CT-3001 W battery testing instrument (50 V 100 A, Shenzhen Neware Electronics Co. Ltd, China) was supplied to perform the charge and discharge of the batteries at room temperature. All the thermocouples were connected to a PC-based data acquisition unit (Agilent 34970 A). The velocity of flowing air through the battery pack was controlled and measured by an adjustable AC power supply and anemograph, respectively.

### 3.2. Design of battery packs

Commercial rectangular  $\text{LiFePO}_4$  battery ( $70 \times 90 \times 27\ \text{mm}^3$ ) with capacity of 12 A h was used in this study. Fig. 2(b) shows the physical model of the BTM with CM-PCMP. The battery pack consisted of six CM-PCMP and five batteries in the pattern of compact sandwich structure. The five batteries were assembled in a series connection. A fan (EBM-PAPST8412 N from EBM-PAPST Group) was used to suck the air into the regular channel from one side of the

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