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Experimental study of a passive thermal management system for high-powered lithium ion batteries using porous metal foam saturated with phase change materials

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HIGHLIGHTS

- Cooling structure for Li-ion battery using foam-paraffin composite was designed.
- Thermal management by air natural convection cannot fulfill battery safety demand.
- Employment of pure PCM dramatically reduced battery surface temperature.
- Integration of copper foam and paraffin further reduced battery temperature.
- Battery surface temperature increased with increase in porosity and pore density.

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ABSTRACT

A highly efficient thermal strategy to manage a high-powered Li-ion battery package within the required safe temperature range is of great demand for electric vehicles (EVs) applications. A sandwiched cooling structure using copper metal foam saturated with phase change materials was designed. The thermal efficiency of the system was experimentally evaluated and compared with two control cases: a cooling mode with pure phase change materials and an air-cooling mode. The results showed that the thermal management with air natural convection cannot fulfill the safety demand of the Li-ion battery. The use of pure PCM can dramatically reduce the surface temperature and maintain the temperature within an allowable range due to the latent heat absorption and the natural convection of the melted PCM during the melting process. The foam-paraffin composite further reduced the battery's surface temperature and improved the uniformity of the temperature distribution caused by the improvement of the effective thermal conductivity. Additionally, the battery surface temperature increased with an increase in the porosity and the pore density of the metal foam.

1. Introduction

Lithium-ion batteries are generally treated as substitutes for nickel metal batteries and lead acid batteries for use in hybrid electric vehicles (HEVs) or electric vehicles (EVs) due to their high power density, stable charge and discharge cycle and relatively long lifespan. These large scale batteries are packed in series or in parallel in some applications that have a greater power demand, and, in this case, the battery temperature during the charge and discharge process must be maintained within an allowable temperature range when using this integrated package to avoid thermal runaway situations due to excessively high (greater than 60 °C) or extremely low temperatures (below 0 °C), which can decrease the battery lifetime, as stated in Refs. [1,2]. Additionally, the temperature uniformity among various cells was demonstrated to be crucial to the battery pack's safety because large temperature differences can cause the capacity of the entire battery pack to decrease [3]. Therefore, a very efficient temperature regulation and thermal management system is necessary for a high-powered Li-ion battery module.

A variety of heat dissipation techniques and designs have been previously reported in the literature. Wu et al. [4] designed a self-contained heat pipe attached to the battery surface to mitigate the temperature increase during discharge and found that the addition of the heat pipe combined with air forced convection reduced the rate of temperature increase and resulted in a more

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uniform temperature distribution. Pesoaran [5] designed a liquid-based thermal management system for batteries in EV applications and measured the battery temperature during the discharge process. The results demonstrated that the cooling efficiency was significantly improved using a liquid-based cooling system. Nelson et al. [6] modeled and compared the thermal control systems for lithium batteries based on an air-cooled and a fluid-cooled method. Their results demonstrated that the transfer fluid was superior to air for cooling the battery. Fan et al. [7] numerically analyzed the thermal behavior of prismatic lithium ion cells within an air-cooled module. They found that reducing the gap between the cells or increasing the velocity of the air resulted in a decrease in the temperature increase.

The thermal efficiency is improved with active thermal management of forced air convection and liquid cooling; however, additional structural complexity or an extra cost associated with the energy supply was required. In the past decades, a thermal management system using organic PCM was preferred. The organic PCM offers advantages of greater latent heat, stable chemical characteristics, a proper phase change temperature and a reasonable price [8]. Sabbah et al. [9] compared the effectiveness of two dissipation modes using air forced air convection and phase change materials under the same discharge condition for 1.5 Ah 18650 commercial batteries. Their experimental results revealed that the PCM cooling system resulted in a better thermal performance compared with the active air at a discharge rate of 1.3C with a stressful 40 °C ambient temperature. Duan and Naterer [10] experimentally investigated a thermal management technique for a lithium ion battery using phase change materials. Their results demonstrated that the battery temperature was reduced to a safe temperature range by means of the PCM. Although PCMs are excellent candidates for thermal storage and management applications, the intrinsic and undesirably low thermal conductivity of most organic PCMs has, to a large extent, restricted their thermal applications in high-energy charge/discharge rate systems [11]. Confronted with this challenge, various solutions to improve the effective thermal conductivity of PCMs have been proposed. Fan and Khodadadi [12] conducted experimental and theoretical studies into thermal conductivity enhancement technologies, including adding extended fins, inserting high thermal conductivity particles and using a porous metallic medium. In EV applications, Kizilel et al. [13] reported that PCMs in combination with expanded graphite outperformed the active air-cooling system at various discharge rates under extreme ambient conditions. Khateeb et al. [14] experimentally investigated four dissipation modes for a 2.2 Ah 18650 cell package and demonstrated that the use of aluminum foam/PCM composite presented an additional decrease in the temperature increase of approximately 5 °C compared with the pure PCM. An efficient cooling technique of encapsulating a PCM with copper metal foam was studied by Li et al. [15]. The experimental results demonstrated that the use of the metal foam can dramatically improve the effective thermal conductivity of the PCM and reduce the surface temperature of the heater.

From a review of the literature, studies investigating the thermal management of high-powered batteries using foam-PCM composites have been inadequate. Additionally, the effects of the geometric parameters of the metal foam on the thermal performance of the batteries are rarely mentioned in previous studies. In this study, a passive thermal dissipation system for high-energy $Li_yMn_2O_4$ batteries using the integration of a metallic copper foam and a PCM was designed. Two additional thermal dissipation modes, including air natural convection and a pure PCM, were also used as reference cases. The thermal behaviors of the system were evaluated by comparing the battery's surface temperature using the three dissipation modes described above. The effects of the morphology parameters of the metal foam were also investigated.

2. Thermal properties of the PCM and the metal foam

Commercial paraffin (RT 44HC) was employed as the organic PCM. The fusion point, the specific heat capacity and the heat of the paraffin were measured using a Differential Scanning Calorimeter (DSC, TA-Q20, USA). The paraffin sample was heated from 20 °C to 80 °C at a rate of 5 °C min^{-1}. Fig. 1 shows the testing results. The fusion point is from 42.76 °C to 49.24 °C, and the latent heat is 270.7 J g^{-1}. The remaining thermal properties are shown in Table 1. Fig. 2 shows the local morphology of the copper foam supplied by ChangSha Lyrun Material Co., Ltd., China. Five foam samples with different porosities (ε) and pore densities (ω, PPI: pore number per inch) were used in the experiment. The effective thermal conductivity (k_e) can be theoretically determined using Eqs. (1)–(4) in Ref. [16]. The geometric parameters and the thermal dynamic properties are shown in Table 2.

$$k_e = \frac{1}{\sqrt{2}(R_A + R_B + R_C + R_D)} \quad (1)$$

$$R_A = \frac{4\lambda}{\left[2e^2 + \pi\lambda(1-e)\right]k_s + \left[4 - 2e^2 - \pi\lambda(1-e)\right]k_f} \quad (2)$$

$$R_B = \frac{(e-2\lambda)^2}{(e-2\lambda)e^2 k_s + \left[2e - 4\lambda - (e-2\lambda)e^2\right]k_f} \quad (3)$$

$$R_C = \frac{\left(\sqrt{2}-2e\right)^2}{2\pi\lambda^2\left(1-2\sqrt{2}e\right)k_s + 2\left[\sqrt{2}-2e-\pi\lambda^2\left(1-2\sqrt{2}e\right)\right]k_f} \quad (4)$$

3. Experimental setup and procedure

Fig. 3 shows the experimental system that consists of three modules: the test section, the charge/discharge module and the data acquisition system. The copper foam-paraffin composite was prepared by infiltrating the liquid paraffin into the pores of the metal foam in a hot water bath. Fig. 4(a) shows the thermal management of the foam-paraffin composite; the battery pack was formed by organizing ten of the foam-paraffin plates and nine of the Li-ion cells with 10 Ah capacity in the pattern of a compact

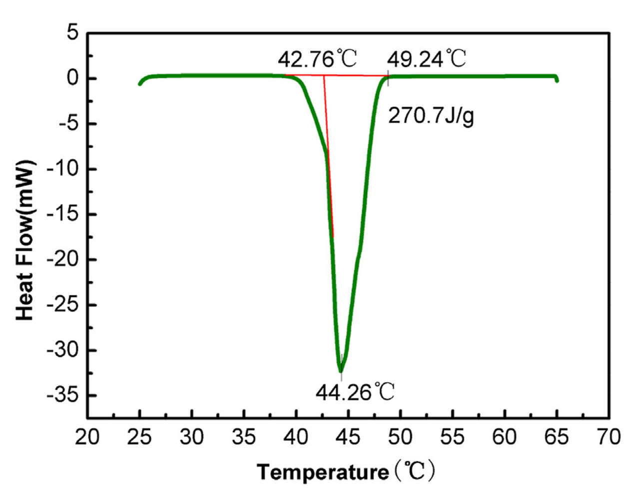

Fig. 1. DSC testing results for the paraffin.