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Research paper

Paraffin and paraffin/aluminum foam composite phase change material heat storage experimental study based on thermal management of Li-ion battery

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HIGHLIGHTS

- Heat storage experiment of paraffin and composite phase change material is studied.
- Composite PCM shows better temperature uniformity than pure paraffin.
- The addition of aluminum foam can increase the heat storage rate of PCM.
- The cooling system with composite PCM for Li-ion battery is experimental studied.
- Paraffin/aluminum foam composite PCM has a good cooling effect on Li-ion battery.

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ABSTRACT

The temperature of battery modules in electric vehicles (EVs) must be controlled adequately to keep within a specified range for optimum performance. The paraffin/aluminum foam composite phase change material (PCM) was investigated experimentally. The experimental results indicate that paraffin/aluminum foam composite PCM has an ideal cooling effect in limiting the temperature rise of the Li-ion battery during the discharge process. The heat storage properties of pure paraffin and the composite PCM are also experimentally studied. The inner temperature distribution of the foam and paraffin is monitored during the melting process. The addition of aluminum foam can largely improve the effective thermal conductivity of the PCM, although its existence suppresses the local natural convection. The experimental results indicate that the use of aluminum foam can speed up the melting process and improve the temperature uniformity of the PCM. When the heat fluxes are 7000 W/m^2 and 12,000 W/m^2, the heat storage time of the composite PCM is 73.6% and 74.4% of that of pure paraffin, respectively.

1. Introduction

Thermal management of Li-ion batteries plays an important role in large power applications in addressing the thermal safety apart from improving the performance and extending the cycle life. The electrochemical performance of the Li-ion battery chemistry, power and energy capability, cycle life and cycle life cost is impacted very much by the operating temperature [1–3]. There exists an optimum operating temperature range with any kind of battery. Therefore, thermal energy management is essential for improving thermal safety performance of the power batteries.

Conventional heat dissipation methods such as forced air-cooling and liquid-cooling have been widely developed. Such thermal management systems can ensure thermal safety, but they tend to make the overall system too bulky, complex and expensive in terms of blower, fans, pumps, pipes and other accessories, which add on to the system weight and parasitic power requirements. They cannot function as a stand-alone system without depending on external power [4]. The current research revealed that the battery thermal management system using phase change material (PCM) could largely overcome these shortcomings [5].

The traditional PCM, such as paraffin, is taken as the most promising because of large latent heat, nontoxic, not corrosive,

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stable and low cost. However, pure paraffin suffers from a low thermal conductivity. High thermal conductivity PCM is demanded strongly in battery thermal management. To resolve the conflict between large heat storage capacity and low thermal conductivity of traditional material, composite PCM is developed. Many materials with high thermal conductivity are added into paraffin to enhance the thermal conductivity [6–9]. If such composite PCM is utilized in the battery thermal management system, the heat absorbing efficiency could be enhanced and the temperature uniformity inside the battery module could be greatly improved. Thus, the battery module can be maintained at an optimum temperature [10]. Aluminum foam is a kind of typical metal material with high porosity, high thermal conductivity and lightweight. It is generally used as the solid skeleton of the composite PCM, in which filled the paraffin wax [11–13]. This kind of composite PCM can improve the effective thermal conductivity on the premise that the density and phase change latent heat of unit volume change negligible [14]. Andrew Mills and Said Al-Hallaj [15] studied on a passive thermal management system with PCM which was designed for a Li-ion laptop battery pack. They found that impregnating expanded graphite (EG) matrix with the paraffin could significantly enhance the thermal conductivity of PCM. Zhonghao Rao et al. [16] pointed out that the thermal resistance of the cell leads to an inevitable temperature difference. It is necessary to improve the thermal conductivity and lower the melting point of the PCM for heat transfer enhancement.

Zhonghao Rao et al. [16] discussed the thermal energy management performance of pure paraffin on cooling commercial rectangular $LiFePO_4$ batteries. W.Q. Li et al. [17] investigated the wall temperature distribution during the melting process of paraffin in copper foams. The surface temperature of the Li-ion battery is controlled by phase change heat storage process of PCM. And some previous studies have shown that the composite PCM with high thermal conductivity aluminum foam matrix has a better cooling effect on Li-ion battery than pure paraffin. Hence, it is necessary to investigate the heat storage properties of the composite PCM itself, such as the inner temperature distribution and the phase change time. However, most previous studies focused on the surface temperature change of Li-ion battery, which is controlled by the composite PCM thermal management system, but not on the heat storage properties of the composite PCM. To figure out how the addition of aluminum foam affects the heat storage process of PCM, the heat storage properties of the composite PCM and pure paraffin are compared in this paper. It could also be references and bases for the further deep research on the performance of the composite PCM on cooling Li-ion battery. The aim of the present work is to experimentally investigate the melting process of paraffin in aluminum foam and its cooling effect on Li-ion batteries. Two experimental tests were built. One test was to measure the internal temperatures of pure paraffin and paraffin/aluminum foam composite PCM. The effect of the addition of aluminum foam on temperature uniformity along different directions and the heat storage rate of the PCM was discussed. The other was to measure the surface temperature of the Li-ion battery with the composite PCM. The effect of the composite PCM on cooling Li-ion battery was also discussed.

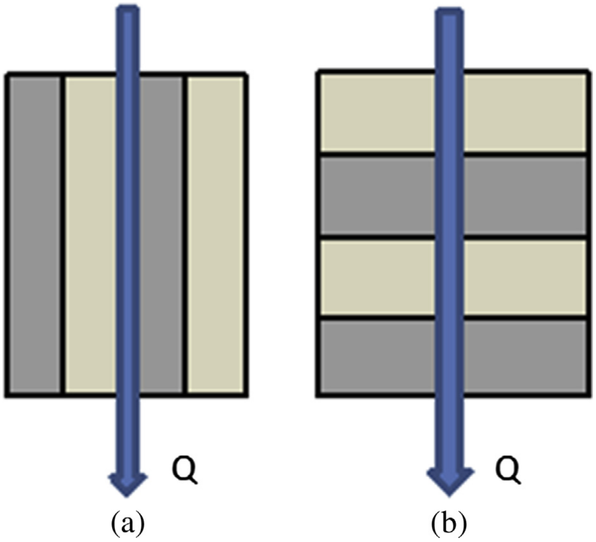

Fig. 1. Effective thermal conductivity model. (a) Parallel Model (b) Series model.

2. Theoretical effective thermal conductivity of paraffin/aluminum foam composite phase change material

Among the calculation models of effective thermal conductivity, series-parallel model of metal material and filler material is relatively simple and available.

Fig. 1 shows two kinds of the idealized model used for dealing with the effective thermal conductivity. As shown in Fig. 1(a), the metal materials and filler materials are alternately parallel arranged. The effective thermal conductivity of the composite PCM is the maximum in this case, which is given in Eq. (1) [18].

$$\lambda_{\max} = (1-\varepsilon)\lambda_{Al} + \varepsilon\lambda_{PCM} \tag{1}$$

As shown in Fig. 1(b), when the heat flux and material are arranged vertically, it is considered that metal material and filler material are in series. The effective thermal conductivity of the composite PCM is the minimum in this case, which is written in Eq. (2) [18].

$$\lambda_{\min} = \frac{\lambda_{Al}\lambda_{PCM}}{\varepsilon\lambda_{Al} + (1-\varepsilon)\lambda_{PCM}} \tag{2}$$

Where λ_{Al} and λ_{PCM} are the thermal conductivities of aluminum foam and paraffin, respectively, and ε is the porosity of aluminum foam. The above two cases are special. The actual effective thermal conductivity is between the two limits. Assuming that there is an angle β between heat flux and the arrangement of materials, the effective thermal conductivity λ_e can be written as Eq. (3). Obviously, once the angle β is determined, the effective thermal conductivity can be determined. The structure of metal foam is similar. For high porosity foam metal materials, the angle β can be determined from the unified equation, which is shown in Eq. (4) [19].

$$\lambda_e = \sqrt{\lambda_{\max}^2 \cos^2\beta + \lambda_{\min}^2 sin^2\beta} \tag{3}$$

$$\tan^2\beta = 16(1-\varepsilon)\varepsilon^3 \frac{\ln(\lambda_{Al}/\lambda_{PCM})}{\left(\frac{\lambda_{Al}}{\lambda_{PCM}} - 1\right)^2} \tag{4}$$

All the four aluminum foam samples used in the experiment had a uniform dimension of 100 mm × 100 mm × 45 mm, namely the volume V_0 of each sample was 45 mL. Solid paraffin was heated to be liquid, which had a volume V_1. Paraffin was heated to be kept liquid. An aluminum foam sample in high temperature was soaked completely in liquid paraffin. After an hour, the heating was stopped. When liquid paraffin completed the solidification, the survival volume V_2 could be measured after removing the aluminum foam sample. Thus, the porosity ε of aluminum foam can be expressed as