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Experimental and numerical investigation of a thermal management system for a Li-ion battery pack using cutting copper fiber sintered skeleton/paraffin composite phase change materials

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ABSTRACT

The thermal safety of lithium-ion battery is a serious issue in its applications. A lithium-ion battery pack cooled by a cutting copper fiber sintered skeleton (CCFSS)/paraffin composite phase change material (PCM) is designed and fabricated. The effect of the CCFSS/paraffin composite PCM on the battery pack temperature is investigated by discharge experiments and compared with natural air cooling, pure paraffin, and copper foam/paraffin composite PCM. A two-equation non-thermal equilibrium model using the enthalpy method is established. The experimental results indicate that the battery temperature difference in the case with pure paraffin exceeds 5 °C, while the CCFSS/paraffin composite PCM effectively enhances the heat transfer performance and maintains the battery temperature differences within 5 °C. The numerical results show good agreement with the experimental data, validating the accuracy of the numerical model. Therefore, the effects of key parameters are investigated and predicted via the numerical model. The heating rate of the battery pack decreases with increases in the number of pores per linear inch (PPI) and the convective heat transfer coefficient. With the increase in the spacing between the cells, the heating rate of the battery pack decreases and the duration of the phase change increases. This work provided a reference for the application of CCFSS/paraffin composite PCM in the heat dissipation of lithium-ion batteries.

1. Introduction

Li-ion batteries are widely applied in electric vehicles because of their outstanding benefits, such as high energy density, low self-discharge rate, high operating voltage, long service life, lack of memory effect, large capacity, and no heavy metal pollution [1–3]. The charging and discharging processes of Li-ion batteries are accompanied by complex chemical reactions that result in considerable amounts of generated heat. If the heat cannot be distributed in time, it will result in a high temperature rise. Excessive temperatures may cause decomposition of the battery material, which can result in safety problems such as burning or even explosions [4–6]. In addition, when the temperature difference between the cells in the lithium-ion battery pack is large, the performance and the lifespan of cells with high temperatures are attenuated rapidly. After multiple charging and discharging cycles, these cells will fail first and cause the battery pack to fail. The required operating temperature of lithium-ion batteries is between −20 and 60 °C and the ideal temperature difference between the cells is 5 °C [7,8]. Therefore, in order to improve the performance and life-span of lithium-ion battery packs, it is extremely important to design a thermal management system for the lithium-ion battery packs.

Conventional heat dissipation modes of lithium-ion batteries include air cooling [9,10], liquid cooling [11,12], heat pipe cooling [13,14], etc. Among these methods, phase change material (PCM) cooling has attracted increased attention [15,16] because it requires no additional equipment for cooling, is energy driven, and has a better thermal buffering effect [17]. Among various kinds of PCMs, paraffin, whose phase change temperature is within the ideal operating temperature range of the lithium-ion battery, presents applicable characteristics such as a large latent heat of fusion (about 200–220 J g^{-1}), stable chemical properties, a small volume expansion ratio, and competitive cost [18]. Therefore, researchers often use paraffin in the thermal management system of Li-ion batteries [19,20]. However, the thermal conductivity of paraffin is poor at only 0.2 W m^{-1} K^{-1} [21], which seriously limits its application in high power Li-ion battery packs.

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Due to the low thermal conductivity of paraffin, researchers have embedded excellent thermal conductivity materials into the paraffin to improve the heat transfer efficiency. Some researchers have increased the thermal conductivity by adding nanomaterials to paraffin, such as carbon nanotubes [22,23], carbon nanofibers [24–26], TiO_2 nanoparticles [27,28], and other metal nanoparticles. However, the addition of nanomaterials increases the viscosity of the paraffin [29], which is not conducive to the flow of liquid paraffin, thereby reducing the heat dissipation effect. Therefore, some researchers have turned to the use of metal foams. Li et al. [7] designed a sandwiched cooling structure using copper metal foam saturated with paraffin and evaluated the thermal efficiency of the system experimentally by comparing the results with data for using cooling with pure paraffin and air-cooling. The results showed that the thermal management with natural air convection did not fulfill the safety requirements of the Li-ion battery, while the use of pure PCM dramatically reduced the surface temperature and maintained the temperature within an allowable range. The foam-paraffin composite further reduced the battery's surface temperature and improved the uniformity of the temperature distribution. Alipanah and Li [30] investigated thermal management systems of lithium-ion battery made from pure octadecane, pure gallium and octadecane–Al foam composite materials numerically. Zhang et al. [15] investigated the flow and heat-transfer characteristics of open-cell aluminum foam/paraffin composite PCM, compared with pure paraffin. The results indicated that the composite PCM was more effective in the thermal management. However, metal foam manufacturing processes are complicated and costly; in addition, the shape of the material is difficult to tailor to specific applications and leakage of the liquid-phase paraffin occurs, leading to decreased heat storage or even safety problems [31]. Moreover, the existence of sealed holes is not conducive to the perfusion of paraffin, which limits the widespread application of metal foams.

Porous metal materials composed of a cutting copper fiber sintered skeleton (CCFSS) with high porosity and good mechanical toughness are easy to fabricate. The pore structure provides not only the skeleton to support the PCMs but also heat transfer channels to enhance the thermal conductivity. Moreover, during the cutting process, scales, grooves, and other rough appearances appear on the surface of the copper fibers, which effectively increases the specific surface area. These features not only increase the bond strength between the PCMs and the CCFSS but also the amount of the PCMs per unit volume. These characteristics demonstrate that the CCFSS has enormous potential for heat dissipation with PCMs in lithium-ion battery packs. However, there is little research on the thermal dissipation of lithium-ion batteries using CCFSS/paraffin composite materials.

In this study, a lithium-ion battery pack cooled by a CCFSS/-paraffin composite PCM was designed and prepared. The effect of the CCFSS/paraffin composite PCM on the temperature of a lithium-ion battery was investigated by a discharge experiment; the results were compared with data for using natural air cooling, pure paraffin, and a copper foam/paraffin composite PCM. In order to further investigate the factors affecting the performance of the thermal management system with composite PCMs, a two-equation non-thermal equilibrium model for lithium-ion battery systems was established. The enthalpy method was implemented to deal with the phase change of the paraffin. Subsequently, the heat transfer of the CCFSS/paraffin composite PCM in the heat dissipation of the lithium-ion battery is simulated by a numerical model. The effects of key parameters such as the number of pores per linear inch (PPI), battery spacing, and the air convective heat transfer coefficient on the battery temperature were investigated to determine the temperature changes of the lithium-ion battery and to optimize the heat dissipation structure. The results would provide a reference for the application of CCFSS/paraffin composite PCM in the heat dissipation of lithium-ion batteries.

2. Experimental

2.1. Model design

In this study, fifteen Panasonic NCR18650PF cells constitute a battery pack; three cells were put in series and five sets of cells in parallel. As shown in Fig. 1, the spacing between adjacent cells is 22 mm. The composite PCM filled the gap between the cells and the overall module size was $110 \times 66 \times 65$ mm^3. The performance parameters of a single cell and the battery pack are shown in Table 1.

2.2. Preparation of CCFSS/paraffin

The copper fibers were fabricated by cutting with a multi-tooth cutter mentioned in previous work [32]. During the metal cutting experiment, multiple cutting edges contact the workpiece at the same time. In this experiment, the multi-tooth cutter was fixed on a lathe (C6132A) using a specially-made fixture; the cutter was installed at an angle of 45°. The workpiece consisted of copper rods with a diameter of 50 mm. The copper fibers were cut into segments with a length ranging from 10 to 20 mm for die forming and sintering. As reported previously [32], The copper fibers were pressed into the sintering mold prior to sintering. The pressed mold was placed into an RXL-12-11 box-type air resistance furnace for sintering.

Porosity is a key parameter of porous material and directly affects the heat transfer performance of composite materials. After sintering, the mass of the CCFSS was weighed. The porosity was determined by Eq. (1).

$$\varepsilon = \left(1 - \frac{M}{\rho V}\right) \times 100\% \tag{1}$$

where ε is the porosity of the CCFSS, M is the mass of the CCFSS, V is the volume of the CCFSS, and ρ is the density of copper.

The porosities of the #1 and #2 CCFSS were so large (96.1% and 91.9% respectively) that liquid paraffin could be added to the

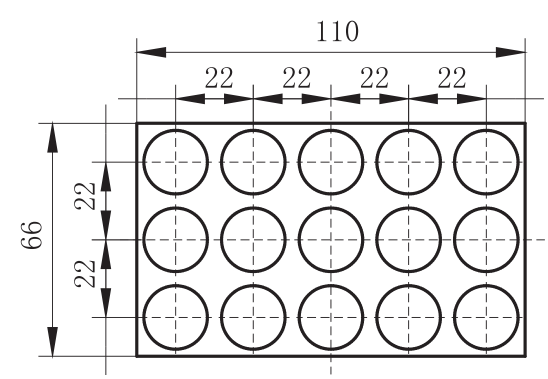

Fig. 1. A schematic of the scale size of the battery pack.

Table 1
Performance parameters of the battery cell and battery pack.

Parameters	Battery cell	Battery pack
Standard voltage/V	3.6	10.8
Nominal capacity	2900 mA h	14.5 A h
Maximum charging current/A	2.9	14.5
Maximum discharging current/A	10	50