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Cutting copper fiber/paraffin composite phase change material discharging experimental study based on heat dissipation capability of Li-ion battery

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ABSTRACT

Paraffin as a phase change material (PCM) is typically used in thermal management of Li-ion batteries. However, the low thermal conductivity of PCMs limits their use in high power devices. Superior thermal conductivity materials are often embedded in PCMs for heat dissipation in the passive thermal management system. In this work, copper fiber/paraffin composite phase change material (CPCM) was prepared based on solid-phase sintering technology. Li-ion batteries in four types of heat dissipation methods (natural wind cooling, filled with pure paraffin, copper foam/paraffin, and copper fiber/paraffin) were tested under different discharging currents. The effect of the porosity of copper fibers was also studied. The result indicates that copper fiber/paraffin CPCM can effectively improve the heat transfer performance and the uniformity of battery temperature within a 2 °C difference. Appropriately increasing the content of copper fiber is favorable to obtain high heat transfer properties of the material. It's predicted that porosity of 90% of copper fiber sintered skeleton offers the best performance of the composite material.

1. Introduction

As an excellent source of power, Li-ion batteries have been successfully applied in hybrid electric vehicles and pure electric vehicles [1] because of the incomparable benefits, such as large energy density, low self-discharge, high working voltage, long service life, no memory effect, large capacity and no heavy metal pollution [2]. The charging and discharging process of Li-ion batteries are accompanied by the production of heat, and it may result in overheating, burning and explosion and other safety issues. Studies [3] show that safety issues raise from a Li-ion battery during operation can be attributed to the variation of its temperature. High temperature may cause the battery materials decompose, thus resulting in burning or even explosion and other safety problems [4]. Additionally, temperature distribution between battery cells should be kept in uniform as far as possible in order to guarantee the efficiency of batteries. Park and Jaura's studies [5] show that the required operating temperature of Li-ion batteries system is between −20 and 60 °C, and the temperature difference between the batteries is within 5 °C. For the sake of safety, a thermal management system is necessary for Li-ion battery module.

Using a PCM for battery passive thermal management system is a feasible approach. Amongst the various kinds of PCMs, paraffin presents applicable characteristics such as large latent heat of fusion (about 200–220 J g^{-1}), stable chemical properties, small volume expansion ratio and competitive cost. Therefore, researchers often use paraffin as a PCM in battery heat dissipation [6]. However, the low thermal conductivity of paraffin with 0.2 W m^{-1} K^{-1} [7] limits their use in high power devices. Thus, superior thermal conductivity materials are often embedded in paraffin to produce a CPCM in the passive thermal management system.

Many researchers embedded materials with high thermal conductivity into PCMs to enhance heat transfer of PCMs. Warzoha et al. [8] embedded herringbone style graphite nanofibers into paraffin to prepare high-conductivity CPCMs. Babepoor et al. [9] used various nanoparticles and their combinations at different concentrations as thermal conductivity promoters to produce modified paraffin samples. Experimental results showed that nanoparticles can improve thermal conductivity of the nanocomposite but the specific heat may be degraded. However, embedding nanomaterials into PCM brought about a sharp increase of their viscosity in liquid phase that resulted in weakening or even eliminating natural convection effect during

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melting, which may overweigh the enhanced heat conduction afforded by the thermal conductivity enhancement [10].

Khateeb et al. [11,12] designed an aluminum foam/paraffin CPCM, which was used for heat dissipation of Li-ion battery pack of electric scooter. The experimental results showed that heat dissipation performance of using aluminum foam/paraffin composite materials was the greatest, comparing with that of other conditions. Tao et al. [13] investigated the latent heat storage performance of metal foams/paraffin CPCM and proposed an optimum structure with porosity of 0.94 and number of pores per inch of 45. Zhang et al. [14] indicated that copper foam could enhance the thermal conductivity of paraffin and there was a quite large temperature difference between the ligament of copper foam and paraffin, which was due to the thermal non-equilibrium effect in heat transfer between the paraffin and copper foam. However, most of metal foams are closed-cell structure, which is not conducive to the filling of phase change material and energy transfer.

Py et al. [15] pressed graphite powder into porous graphite with different porosity and they adsorbed paraffin into new kind of phase change materials by capillary force. Comparing with the pure paraffin thermal conductivity of 0.24 W m^{-1} K^{-1}, the thermal conductivity of CPCM was up to 4–70 W m^{-1} K^{-1}. So the thermal conductivity performance was significantly improved. Jiang et al. [16] indicated that expanded graphite incorporation dramatically enhanced the thermal conductivity of CPCM and lead to a significant decrease in the temperature rise of Li-ion batteries. But liquid PCM leakage, which decreased with an increase in EG loading, occurred during phase transition. Samimi et al. [17] demonstrated that the presence of carbon fibers increased the effective thermal conductivity of PCM and hence influenced temperature distribution within the cell. Zhou et al. [18] developed a sintered copper fiber felt with metal fiber as the raw material by using a solidphase sintering method. Coarse antler surface structure on the surface of copper fibers made by multi-tooth cutter have high specific surface area and surface energy, so the copper fibers are suitable for heat dissipation. Moreover, a great deal of surface microstructures on copper fibers enhance bonding strength during sintering, which results in a high thermal conductivity. Thus, copper fibers with numerous surface microstructures have a significant potential to enhance thermal performance of PCMs. However, few studies have paid attention to heat transfer enhancement technology combined with copper fibers and PCMs.

In this work, the copper fiber sintered skeleton is prepared to enhance thermal performance of paraffin. The copper fiber sintered skeleton was made of cutting copper fibers, and it can support the Li-ion battery and strengthen the internal heat transfer of paraffin. Li-ion batteries in four types of heat dissipation methods (natural wind cooling, filled with pure paraffin, copper foam/paraffin, and copper fiber/paraffin) were tested under different discharging currents. In addition, the influence of different porosity of copper fibers was also experimentally investigated.

2. Experimental

2.1. Module size parameters design

In this paper, 15 Panasonic NCR18650PF cells consisted of a battery pack, which every three cells were put in series and five set of cells in parallel. 18650 means that the diameter and the height of cylindrical battery cell is 18 and 65 mm, respectively. As shown in Fig. 1, the battery cells were placed at equal intervals with three lines and five columns, and the distance between adjacent batteries was 22 mm. CPCMs were filled in the gap between the batteries and the overall module size was 110 × 66 × 65 mm. The battery cell and battery module performance parameters are shown in Table 1.

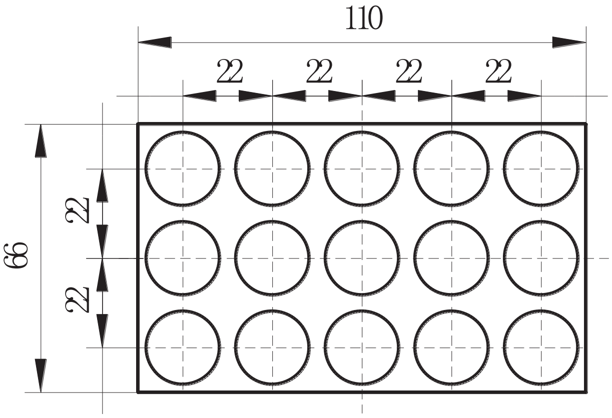

Fig. 1. The schematic of the scale size of battery pack.

2.2. Cutting continuous copper fibers

The copper fibers were fabricated by cutting with a multi-tooth cutter. The structure of multi-tooth cutter is as shown in Fig. 2. It can be seen in Fig. 2, serrate grooves are machined at equal intervals in nominal flank of the cutter. During the metal cutting experiment, multiple cutting edge could contact with the workpiece at the same time. Continuous multiple metallic fibers were machined, and the efficiency was improved. In addition, metallic fibers machined in this method can obtain better tensile strength and toughness.

In this experiment, tooth profile of multi-tooth cutter was made of wire-cutting processing, and the material was high speed superhard steel. The cutter tooth width was m = 0.3 mm and cutter tooth depth was n = 0.2 mm. Multi-tooth cutter was fixed on the lathe C6132A with specially-made fixture, and the cutter was installed with 45° and the height was adjusted. The workpiece was copper rods with diameter of 50 mm. Specific cutting parameters were as follows: the rotational speed was 160r min^{-1}, the feeding speed was 0.2 mm r^{-1}, and the back engagement was 0.2 mm. The processing site that multi-tooth cutter machined copper fibers is as shown in Fig. 3. The copper fibers were cut into segments with length range from 10 to 20 mm for die forming and sintering.

2.3. Manufacturing copper fiber sintered skeleton

The copper fibers needed to be pressed into the sintering mold before sintering. The sintering mold consisted of cover plate, stainless steel mandrel (with diameter of 18 mm), the core fixed board, cavity and baseboard, as shown in Fig. 4(a). To ensure space between mandrels consistent, 15 holes of Φ18 mm were drilled on the core fixed board and cover plate. Before filling with copper fibers, the mandrel and cavity inside needed to be sprayed release agent so that copper fiber sintered skeleton could be demoulded easily after sintering. Then the cover plate was opened, and copper fibers were filled around the stainless steel mandrel and were compacted. And then the cover plate was covered and the four mounting bolts were locked. The object figure is as shown in

Table 1
Table of the battery cell and battery module performance parameters.

Parameters	The battery cell	The battery module
Standard voltage/V	3.6	10.8
Nominal capacity	2900 mAh	14.5 Ah
Maximum charging current/A	2.9	14.5
Maximum discharging current/A	10	50