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Thermal conductivity enhancement of phase change materials with form-stable carbon bonded carbon fiber network



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HIGHLIGHTS

GRAPHICAL ABSTRACT

- Carbon bonded carbon fibers monoliths were prepared by slurry molding method.
- PCM composites were fabricated with vacuum impregnated paraffin into CBCF monoliths.
- PCM composites were with greatly improved thermal conductivity and formstability.
- The thermal conductivities of PCM composites were greatly increased by 18 to 57 times over pure paraffin wax.

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ABSTRACT

Carbon bonded carbon fiber (CBCF) monoliths were prepared from graphite fibers with high thermal conductivity, to promote heat transfer and to stabilize the shape of phase change material (PCM). The CBCF monoliths with density from 0.09 to 0.39 g/cm³ were filled with paraffin wax to form PCM composites. Due to the anisotropy of the CBCF material, the PCM composites had varied thermal conductivities with their directions. Results showed that the in-plane thermal conductivity of the PCM composites was markedly improved by 18 to 57 times over the pure wax, depending on the density of CBCF composites, while the out-of-plane thermal conductivity was also increased by 3.7 to 5.5 times. In addition, the improvements in thermal conductivity showed almost linear relationship with the volume fraction of carbon fibers in the PCM composites. The charging time of the composites with the high CBCF density was reduced to one quarter of pure paraffin, while the discharging time was about one sixth. The apparent enthalpy of PCM composites was found to vary with the loadings of paraffin wax, by differential scanning calorimetry (DSC). After 40 cycles, the wax loadings in the PCM composites were retained at 56–70%. © 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Over the past a few decades, the energy demand has grown at an unprecedented rates globally with rapid economic and social

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https://doi.org/10.1016/j.matdes.2018.01.052 0264-1275/© 2018 Elsevier Ltd. All rights reserved. developments. In the face of depletion of fossil resources and growing environmental awareness, a large flux of research activities have devoted to developing technologies for harnessing renewable energies. A very important concern in the utilization of these new forms of energy is how to bridge the gap between energy generation and consumption [1]. Thermal energy storage (TES) system is considered to be an attractive option as it can store excess energy at peak times and release at off-

Table 1Some properties of paraffin wax.

| Materials | Density ρ (g/cm ³) | Melting point (°C) | Specific heat capacity (J/(g·K)) | Thermal conductivity (W/(m·K)) | Latent heat (J/g) |
|--------------|-------------------------------------|-----------------------|-------------------------------------|-----------------------------------|----------------------|
| Paraffin wax | 0.9 | 58–60 | 2.7 | 0.24 | 212 |

peak times. The TES technology can be classified into two categories: sensible heat storage (SHS) and latent heat storage (LHS). The LHS system using phase changing materials (PCMs) is particularly attractive since it provides high energy density at relatively low mass and volume [2,3]. Both storage and release of energy in PCM is based on the phase change enthalpy at nearly constant temperature. Wide availability in terms of phase transition temperatures and fusion heats allows PCM-based LHS systems to be used in many fields, such as solar energy storage [4], building construction materials [5,6], thermal management for electronic devices [7,8], automobiles [9] and food industry [10].

Due to low thermal conductivity (e.g. between 0.1 and 1 W/m·K), many promising PCMs are unable to be employed in practical applications [2], leading to prolonged charging and discharging times. Various attempts have been made to improve heat transfer rates in PCMs. Among viable materials options (including Copper [11,12], aluminum [13], nickel [14], stainless steel [15] and carbon), carbon-based materials have attracted significant attentions because of their high thermal conductivity, low density, chemical inertness and compatibility with various PCMs. Two methods were generally employed to incorporate conductive promoters, i.e. the dispersion of high thermal conductivity micro/nano fillers and the impregnation of PCMs into porous and conductive structure. With rapid advancement in nanotechnology, nanostructured carbon materials have been widely tested in fluid-like dispersion systems [16–21]. However, there are a number of unsolved issues, including limited loadings and therefore limited enhancements, poor homogeneity and stability. Recently it has been recognized that an effective and stable heat transfer network is important in realizing high thermal conductivity with PCM composites [22,23]. If designed properly, the continuous phase in the composites would also serve as support to hold or confine flowing PCMs and hence to stabilize their shape.

Along the direction, carbon promoters with porous or percolated structure had been proposed to make more conductive PCM composites [22]. Carbon-based nanomaterials, including carbon nanotubes, carbon nanofibers have been examined, forming PCM composites with thermal conductivity normally below 0.7 W/(m-K) even at high loading [22]. On the other hand, expanded graphites (EG) have also been made into PCM composites with loadings from 2 to 40 wt%, giving thermal conductivity up to 1 to 2 order of magnitude [24-26] higher than that of nanocarbonbased composites. Although the separation of liquid PCMs from EG is a major concern, considerable enhancements in thermal conductivity as high as 2.24 to 5.76 times have been achieved without leakage on paraffin-based composites containing 25 wt% EG [27]. Also, graphite foam is known to have superior heat transfer rate [28-30], but optimum loadings of PCMs have been hard to achieve at this moment because of relatively high density and closed porosity. Additionally, the graphite foam is difficult and expensive to produce, especially with large size.

Although carbon fibers (CF) are widely available and thermal conductivity in fiber axis sometimes can be higher than copper, their applications to PCMs have been very limited so far, mostly to free and randomly dispersed systems [31–33]. Some known problems include inhomogeneity due to poor dispersion and instability during chargedischarge cycles, acting as major hurdles to a number of practical applications. With the most recent CF-PCM composites made by Nomura and his coworkers, significant improvements in thermal conductivity were achieved by 7–30 times over pure PCMs, with CF-PCM composites compacted by hot-press method [23]. Further improvements have been made to achieve higher conductivity and more stable cycles, by adding more fibers and small partiles of low melting metal (In) to form "welded metal bonds" between random fibers [34]. However, the use of metal particles not only increased the relative density and cost, but also they may cause handling, contamination and potential compatibility problems with both carbon and PCM materials in long term service.

In this study, a novel PCM composite with high thermal conductivity was prepared by incorporating carbon bonded carbon fiber (CBCF) monolith into PCM to overcome some problems discussed above. Paraffin wax was selected as the PCM because of its low cost, reasonable energy density, negligible supercooling and relatively inertness. The CBCF monolith was prepared by bonding random carbon fibers with polymer binder to form a highly stable network after carbonization [35]. The carbon fibers used have high thermal conductivity and are made from mesophase pitch. The PCM composites were obtained by soaking paraffin wax under vacuum. Because conductive carbon fibers can provide effective and stable conduction paths within the CBCF monolith, the thermal conductivity of the PCM composites was markedly increased by 18 to 57 times. Additionally, the PCM composites based on this CBCF monolith have advantages of light weight and dimensional stability.

2. Experimental

2.1. Materials

Paraffin wax was used as the phase change materials. Some general properties of the paraffin were listed in Table 1. The chopped carbon fibers from mesophase pitch (XN-100-03Z, Nippon Graphite Fiber) were used to produce carbon bonded carbon fiber (CBCF) composites with networked reinforcement and open porosity. Table 2 lists some properties of the carbon fibers. Phenolic resins (PF-4292, Changchun Plastics Co., Ltd) were used as a binder, their density was 1.2 g/cm³. The carbon yield of the binders alone after a heat treatment of 800 °C was 57 wt%.

2.2. Sample preparation

The CBCF monolith was prepared following a slurry molding method which has been reported elsewhere [36]. Briefly, carbon fibers and binder resin particles were mixed at certain ratio with water to make a slurry. The filtrates of the slurry was dried and cured in a cylindrical mold to make resin-bonded composites. CBCF composites were then obtained after carbonization at 800 °C in a nitrogen atmosphere. The size of CBCF samples is 25.4 mm in diameter and 10 mm in height. To control the bulk density of the CBCF monolith, different loads were applied in the molding through the curing of the resin.

Some properties of carbon fibers used to produce carbon bonded carbon fiber (CBCF).

Table 2

| Materials | Density | Thermal conductivity | Specific heat capacity | Diameter | Length |
|--------------|----------------------|----------------------|------------------------|----------|--------|
| | (g/cm ³) | (W/(m·K)) | (J/(g·K)) | (µm) | (mm) |
| Carbon fiber | 2.22 | 900 | 0.69 | 10 | 3 |

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