



Heat transfer characteristics of phase change nanocomposite materials for thermal energy storage application



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ARTICLE INFO

Article history:

Received 16 January 2014

Received in revised form 17 March 2014

Accepted 19 March 2014

Keywords:

Heat transfer enhancement

Carbon additives

Nanocomposites

Phase change materials

ABSTRACT

Three phase change nanocomposite materials made of stearic acid and different carbon additives (multi-walled carbon nanotube-MWCNT, graphene, graphite) are prepared to enhance the heat transfer performance for thermal energy storage applications. The SEM analysis shows that the carbon additives are uniformly distributed in the based phase change material of stearic acid, and the DSC analysis reveals that the melting onset temperature of nanocomposites shifts to a lower temperature. The experimental results indicate that the addition of carbon additives can improve the heat conduction of stearic acid effectively, but it also weakens the natural convection of stearic acid in liquid state. The graphite-based nanocomposite has the highest heat transfer performance during both the charging and discharging processes among three kinds of nanocomposites. In comparison with the pure stearic acid, the charging and discharging rates are improved by about 37% and 320%, respectively by using the graphite-based nanocomposite with the content of 5.0%. It appears that the graphite is a more effective additive for enhancing the heat transfer of phase change materials compared with MWCNT and graphene although the former additive has a lower thermal conductivity than the latter additives.

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1. Introduction

Latent heat thermal energy storage has been considered as an effective technology for adjusting the instability and time-discrepancy between energy supply and demand [1]. Among different heat storage methods, latent heat storage using phase change material (PCM) has gained increasing attentions as the recognition of energy-saving and the utilization of renewable energy in recent years, and it has great potential to play an important role in energy management, particularly in solar energy systems [2–7]. However, poor heat transfer performance is the common obstacle for most latent heat thermal energy storage systems due to the low thermal conductivity of the PCMs employed [8].

In order to enhance the heat transfer performance of thermal energy storage application, various techniques have been investigated to improve the poor thermal conductivity of PCM [9–12]. In general, these different techniques can be classified into two types of methods: enlarging the heat-exchange area by designing heat exchanger with finned configuration and enhancing the

thermal conductivity of stored material by developing new phase change composite using additives. In the past decade, phase change composites made of PCMs and some additives with high thermal conductivities have been extensively discussed in different thermal energy storage systems. The potential additives mainly include porous graphite matrix [13,14], porous metallic matrix [15,16], dispersing metal particles [17,18], microencapsulated materials [19,20], inserting carbon fibers [21,22], carbon nanotube [23,24], and other matrix [25].

A lot of work has been performed on the heat transfer enhancement of phase change materials using the composites made of PCMs and additives [12]. However, little attention has been focused on the comparison of thermal performance among different potential additives. As a result, it is usually difficult to judge which kind of additives is better and more beneficial to improve the thermal conductivity of a PCM among various additives. Moreover, although the same additive and PCM are used for thermal energy storage, there usually exists large difference in the magnitude of heat transfer enhancement according to the different literatures obtained from different researchers. For example, Py et al. [26] found that the addition of expanded graphite with mass fraction of 4% could improve the thermal conductivity of pure paraffin by 17–291 times according to the anisotropy characteristic of

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Nomenclatures

T	temperature [°C]	DSC	differential scanning calorimeter
T_e^f	extrapolated end temperature during freezing phase [°C]	PCM	phase change material
T_e^m	extrapolated end temperature during melting phase [°C]	PVP	poly vinyl pyrrolidone
T_o^f	extrapolated onset temperature during freezing phase [°C]	MWCNT	multi-walled carbon nanotube
T_o^m	extrapolated onset temperature during melting phase [°C]	SA	stearic acid
		SEM	scanning electron microscope
		TEM	transmission electron microscope

graphite. Mills et al. [26] reported that the thermal conductivity of the paraffin/graphite composite was about 83 times higher than that of pure paraffin. Xia et al. [28] showed that the thermal conductivity of pure paraffin could be improved by 12 times by using the addition of expanded graphite with mass fraction of 10%. Zhong et al. [29] reported the thermal conductivity of compressed expanded natural graphite (CENG)/paraffin composite can be improved by 28–180 times compared with the pure paraffin wax. Wang et al. [23] found the thermal conductivity of paraffin wax both in liquid and solid states could be improved by 35–40% using MWCNT with mass fraction of 2.0%. Mei et al. [24] showed that the heat transfer rate could be enhanced by 1.7–1.8 times by absorbing capric acid into halloysite nanotubes and graphite compared with the pure PCM. These differences may be attributed to the different manufacturing procedures of composites and different operating conditions during their experiments. In this case, it is difficult to get accurate information by comparing those results obtained from different additives. Thus, it is a desirable work to compare and judge the contribution of heat transfer enhancement of different additives for a phase change material at same working conditions.

In this paper, three phase change nanocomposites are prepared and compared for latent heat thermal energy storage applications by using different carbon additives, namely, multi-walled carbon nanotube (MWCNT), graphene, and graphite. These different carbon matrices are used as inert additives for stearic acid (SA) to fabricate MWCNT-based, graphene-based, and graphite-based phase change nanocomposites, respectively. The purpose of this paper is to evaluate and compare the heat transfer enhancement of the phase change nanocomposites using different carbon additives. The thermophysical properties of these nanocomposites are firstly characterized and analyzed by a scanning electron microscopy (SEM) and a differential scanning calorimeter (DSC), and then the thermal conductivities of these nanocomposites are measured by Hot Disk thermal constants analyzer. Finally, the charging and discharging performances of these different phase change nanocomposites are investigated and compared at the same working conditions using a simple experimental test unit for latent heat thermal energy storage.

2. Experimental energy storage test unit

The manufacturing processes of phase change composites made of porous matrix and PCMs have been reported by many researchers, and a similar method is employed in the paper to fabricate the MWCNT-based, graphite-based, and graphene-based latent heat storage nanocomposites as described in the previous literature [30]. A little amount of Poly Vinyl Pyrrolidone (PVP) is used as a dispersing additive to assure a good dispersion of these carbon additives in liquid stearic acid using a stirring machine with ultrasonication. For every phase change nanocomposite, three samples with different volume fractions of carbon additive (0.5%, 1.0% and 5.0%) are prepared in order to evaluate the effects of different

contents of the additive on the heat transfer enhancement of the PCM. These phase change nanocomposite samples are firstly tested their stabilities during many charging/discharging cycles, and then the thermal performances of these latent heat storage nanocomposites are investigated and compared with the pure PCM by using an experimental setup and thermal analyzers.

Fig. 1 shows the schematic diagram of latent heat energy storage system for phase change nanocomposites using stearic acid with different carbon additives. The experimental test rig mainly consists of a low-temperature thermostatic water bath, a high-temperature thermostatic water bath, a heat storage tank, two flow meters, a data logger, and several controlled valves. Latent heat storage nanocomposite is filled in the heat storage tank, and its working temperature is automatically controlled by the two thermostatic water baths with an accuracy of 0.1 °C with the help of an electrical heater and a compressor chiller. The heat consumed by phase change nanocomposite is supplied by the hot water from the high-temperature thermostatic water bath during the charging process; whereas, the heat released by phase change nanocomposite is removed by the cooling water from the low-temperature thermostatic water bath during the discharging process.

In order to evaluate the effects of different carbon additives on the heat transfer enhancement of the pure PCM, an equivalence mass of 850 g stearic acid is maintained as a baseline for MWCNT-based, graphene-based, and graphite-based phase change nanocomposites during the experiments. To identify the thermal performance of these latent heat storage nanocomposites, two flow meters with an accuracy of 1.5% are used to measure the mass flow of circulated water during the charging and discharging phases. Three thermocouples are placed in the heat storage tank to measure the temperature of phase change nanocomposite, and the installing position of thermocouples is shown in Fig. 1. Two thermocouples are utilized to measure the inlet and outlet water temperatures. The measurement error of temperature is within ± 0.5 °C by using four-wire type PT100 platinum resistance sensor. The heat storage tank and thermostatic water baths are insulated in order to reduce the heat losses to the ambient.

A parameter is defined and used to evaluate the effects of heat transfer performance of the pure PCM by using these different carbon additives. The heat transfer enhancement rate for the phase change nanocomposites during the experiments is defined as:

$$\Delta t_h = (t_1 - t_2)/t_1 \times 100\% \quad (1)$$

in which t_1 is the required time that the pure stearic acid reaches its extrapolated onset phase-change temperature, and t_2 is the required time that the nanocomposite attains its extrapolated onset phase-change temperature. For all storage materials, the extrapolated onset phase-change temperatures during the melting and freezing phases can be determined according to the DSC analysis.

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