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Investigation on the thermophysical properties and transient heat transfer characteristics of composite phase change materials

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ABSTRACT

In this paper, the thermophysical properties and transient heat transfer characteristics of composite phase change materials (CPCMs) were investigated numerically and experimentally in details. Two kinds of micro-encapsulated phase change materials (MEPCMs) paraffin with melting temperatures of 28 and 37 °C, respectively, were employed in this paper. The CPCMs were fabricated by intercalating expanded graphite (EG) with average diameter of 45 m into MEPCMs. The addition amount of EG were 10%, 30%, and 50% in weight. The thermophysical properties, including density, thermal conductivity and specific heat, of the CPCMs were measured and the latent heat and specific heat were calculated from data with differential scanning calorimetry (DSC). In the experiment, the square enclosure has a cross-section dimension of 100 by 100 mm and it was 15 mm in thickness. The top side wall of the enclosure was heated with isothermal cooling on the bottom side wall while the remaining side walls were thermally insulated. The numerical model which is designed to meet the conditions of the experimental parameters was employed to examine the transient heat transfer characteristics for the CPCMs in the enclosure. Results show that MEPCMs with increasing EG would increase the thermal conductivity and the heat transfer rate. However, the specific heat of CPCMs would decrease. The numerical predictions agree well with the experimental data. In addition, the results disclose that the CPCMs could enhance the rate of heat transfer and energy storage, but minor loss in total energy storage.

1. Introduction

Due to energy crisis, the application of energy storage technology draw great attention worldwide. Because various green energies are intermittent, therefore, energy storage technology plays an important role of storing and releasing energy. Energy storage methods include thermal storage, chemical storage, and others. The thermal storage includes sensible heat storage and latent heat storage (phase change). The sensible heat storage is carried out by utilizing the natural heat storing capacity of materials, while phase change energy storage is carried out by storing and releasing latent heat during the phase change (solid–liquid, solid–solid, gas–liquid) [1]. For the past decades, phase change materials (PCMs) have been investigated for many applications, such as the solar energy systems [2], energy efficient buildings [3], and electronic cooling [4], because of the energy storage density during thermal heating and cooling processes.

According to literatures related to PCM, the application of PCM was found mostly in the study of building materials. In the investigation of Kara and Kurnuç [5], a PCM wall includes phase change material (PCM) as a heat storage medium. They found that no overheating problems for the PCM wall were observed in the summer. Oliver [6] studied the thermal behavior of a new construction material: gypsum board containing 45% by weight of PCMs reinforced with additives. He had shown that a 1.5 cm-thick board of gypsum with PCMs stores 5 times the thermal energy of a laminated gypsum board, and the same energy as a 12 cm-thick brick wall within the comfort temperature range (20–30 °C). Zhou et al. [7] numerically investigated reduction of the mismatch between energy supply and demand through the traditional building structures incorporated with PCMs in order to minimize energy consumption (cooling/heating energy). They adopted a heat capacity model to consider the effect of latent heat of PCMs. Their results indicated that the latent heat of PCM wall with more than 50 kJ/kg had

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Nomenclatures

C	specific heat
Fo	Fourier number
H	plate thickness
h	latent heat
HF	heat flow
k	thermal conductivity
L	length
Q_c	dimensionless heat transferred via the bottom plate to the CPCM
Q_h	dimensionless heat transferred via the top plate to the CPCM
Q_{net}	net accumulated heat storage
Q_o	maximum heat stored
$\dot{q}$	heat flux
S	slope formed by two peaks in DSC
T	temperature
V	volume
w	weight
X, Y	non-dimensional direction coordinate
x, y	directional coordinate

Greek

α	thermal diffusivity
δ_A	side wall thickness
ρ	density
τ	time
θ	dimensionless temperature

Subscript

Al	aluminum
bl	blank pans
c	for bottom plate
EG	for EG
h	for top plate
i, j	grid position index
M	melting
ME	for MEPCM
m	for CPCM
p1	heating rate of 1 °Cmin^{-1}
p3	heating rate of 3 °Cmin^{-1}
q	substances of acrylic, aluminum, and CPCM
R	reference material
r	heating rate of r °Cmin^{-1}
s	sample material

a higher economic value.

However, there are few mature PCM-based applications currently. One of the most important reasons is that there are few suitable PCMs. In addition, the thermal conductivity for PCMs is very low. In order to increase the thermal conductivity of PCM, some researchers employed additives with high thermal conductivity materials. Fang and Zhang [8] blended an organic PCM with an organic-modified montmorillonite and found that the thermal characteristics of the composite PCM were close to those of the pure PCM. They also showed the composite PCM exhibited higher heat transfer rate owing to the combination with montmorillonite. He et al. [9] demonstrated that the n-alkanes/silica composites achieved a high thermal conductivity, low supercooling, and good work reliability as a result of the encapsulation of n-alkanes with highly thermal conductive inorganic silica. They also presented that the thermal stability of the composites was also improved due to the protection of silica wall toward the encapsulated n-alkanes. Li et al. [10] used high-density polyethylene (HDPE)/wood flour compound as supporting material and micro-encapsulated paraffin (MEP) as latent heat storage medium by blending and compression molding method for potential latent heat thermal energy storage (LHTES) applications. Micro-mist graphite (MMG) was added to improve thermal conductivities. They found that the thermal conductivity of the form-stable PCM was increased by 17.7% by adding 8.8 wt% MMG. The results of mechanical property test indicated that the addition of MMG has no negative influence on the mechanical properties of form-stable composite PCMs. Karaipekli et al. [11] evaluated the effect of expanded graphite (EG) and carbon fiber (CF) as heat diffusion promoters on thermal conductivity improvement of stearic acid (SA), as a PCM. The thermal conductivities of SA/EG and SA/CF composites were measured with addition of EG and CF in different mass fractions (2%, 4%, 7%, and 10%) by using hot-wire method. Their results indicated that the melting times of composite PCMs were reduced significantly with respect to that of pure SA. Furthermore, the latent heat capacities of the SA/EG and SA/CF (90/10 wt%) composite PCMs were determined by differential scanning calorimetry (DSC) technique and compared with that of pure SA. Li et al. [12] prepared a novel microencapsulated phase change composite of paraffin@SiO_2 with in situ emulsion interfacial hydrolysis and polycondensation of tetraethyl orthosilicate (TEOS). The paraffin was encapsulated in a SiO_2 shell, and there is no chemical reaction between them. They showed that the paraffin@SiO_2 composite is composed of quasi-spherical particles with diameters of 200–500 nm. In addition, the high heat storage capability and good thermal stability of the composite enable it to be a potential material to store thermal energy in practical applications.

In the massive amount of researches of PCMs, paraffin wax was regarded as the most promising material due to its desirable characteristics, such as a high latent heat of fusion, negligible super-cooling, wide option of the appropriate melting temperature, stable chemical and physical properties, and low vapor pressure in the melting process [13,14]. However, there would be material loss during melting process, and void formation during solidification process for PCMs. Generally, paraffin waxes are kept in a closed tank or container during heating to suppress wax leakage. There were many researchers examining thermal conduction enhancement by using porous media [15], fins [16], and steel meshes [17]. For some researchers used additives with high thermal conductivity materials to increase the thermal conductivity of paraffin. Zhang et al. [18] showed that the thermal conductivity of the shape-stabilized PCM can be improved greatly by adding exfoliated graphite. The shape-stabilized PCM was made of paraffin as the phase change material and styrene-butadiene-styrene (SBS) as the supporting material. Their results indicated that the mass fraction of exfoliated graphite was 20%, the thermal conductivity is 221% higher than the original. Kim and Drzal [19] investigated properties, such as electric conductivity, thermal conductivity and latent heat storage, of paraffin with exfoliated graphite nanoplatelets (xGnP) CPCM. He discovered that the thermal conductivity of paraffin/xGnP CPCMs was increased as xGnP loading contents. Besides, the latent heat of paraffin/xGnP composite PCMs did not decrease as loading xGnP contents to paraffin. They concluded that xGnP can be considered as an effective heat-diffusion promoter to improve thermal conductivity of PCMs without reducing its latent heat storage capacity in paraffin wax. Zhong et al. [20] used compressed expanded natural graphite (CENG) matrices with different densities to increase the thermal property of paraffin wax. Their results indicated that the thermal conductivity of the composites can be