International Journal of Heat and Mass Transfer 94 (2016) 191–198

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental and numerical study on transient thermal energy storage of microencapsulated phase change material particles in an enclosure

C.J. Ho [a,*], Chia-Cheng Chen [a], Wei-Mon Yan [b,*]

[a] Department of Mechanical Engineering, National Cheng-Kung University, Tainan 70101, Taiwan
[b] Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 10608, Taiwan

ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form 9 November 2015
Accepted 11 November 2015
Available online 7 December 2015

Keywords:
Microencapsulated phase change material
Transient thermal energy storage
Experimental and numerical study
Enclosure

ABSTRACT

This work aims to examine, via a complementary approach of experimental measurement and numerical simulation, transient characteristics of thermal energy storage in an enclosure filled with microencapsulated phase change material (MEPCM) particles. The core phase change material of the MEPCM is n-octadecane with melting temperature about $T_M = 24$ °C. The two vertical surfaces of the enclosure are, respectively, maintained at hot and cold temperatures, while the horizontal surfaces are kept thermally insulated. The study has been performed for nine sets of the hot and cold wall temperatures with the corresponding dimensionless parameters ranges: Stefan number $Ste_m = 0.063–0.251$; subcooling factor $Sb_c = 0.0–0.75$. To further elucidate the relevant heat transfer characteristics, numerical simulations have been carried out based on a mathematical modeling of the experimental configuration considered. The results disclosed that the faster melting is experienced for the system with higher Stefan number and the subcooling number is the main parameter to dominate the thermal latent heat storage of the MEPCM system. Besides, the dimensionless accumulated energy through the hot wall Q_h^* is well correlated with the relevant parameters, including the Stefan number St_m, the subcooling parameter Sb_c, and the Fourier number Fo.

1. Introduction

Nowadays, thermal energy storage systems are crucial for reducing dependency on fossil fuels and also for minimizing CO_2 emissions [1] by using sensible heat storage or latent heat storage. Latent heat storage is more attractive than sensible heat storage because of its high storage density with smaller temperature swing [2,3]. Microencapsulated phase change materials (MEPCMs) have been widely used as latent heat storage materials. The use of MEPCM is one of the most efficient ways of storing thermal energy due to the higher effective specific heat resulted from latent heat absorption/release associated with melting/freezing behaviors within the PCM particles. The heat transfer characteristics of phase change materials (PCMs) have received a growing attention in numerous technical processes and engineering applications in the past decade [4–15]. Such references include the latent-heat thermal energy storage [4–7], thermal protection [8–10], active/passive electronic cooling [11–15], textile [16–18], as well as solar energy utilization [19,20]. Recently, the characteristics of fluid flow and heat transfer in a rectangular cavity filled with microencapsulated phase change materials (MEPCMs) were investigated numerically by Sabbah et al. [21]. Their predicted results indicated considerable heat transfer enhancement (up to 80%) at the considered operating conditions. The heat transfer enhancement is a result of the MEPCM latent heat and the increased volumetric thermal expansion coefficient owing to MEPCM volume change during melting. Ho and Gao [22] performed melting experiments in a vertical square enclosure packed with a solid–liquid phase change material (PCM) dispersed with nanoparticles (Al_2O_3). They indicated that the influence of the solid subcooling through the unmelted PCM in the enclosure can become further strengthened by the enhanced thermal conductivity with the fraction of Al_2O_3 nanoparticles in the enclosure. The transient transport processes associated with melting of a phase change material (PCM) placed inside a vertical rectangular enclosure with a free-moving ceiling was examined experimentally and numerically by Ho et al. [23]. They presented the corrected displacement of the top ceiling subjected to various thermal conditions.

Although the above investigations studied the heat transfer in enclosures with PCM, to the best of the authors' knowledge, few studies in the literature systematically examined the transient

* Corresponding authors.
E-mail addresses: cjho@mail.ncku.edu.tw (C.J. Ho), wmyan@ntut.edu.tw (W.-M. Yan).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.11.055
0017-9310/

Nomenclature

A_p	surface area of MEPCM particle (m^2)
Bi_p	Biot number, $h_p\ dp/k_p$
c	specific heat (J/kg K)
C_F	Forchheimer's constant
d_p	diameter of MEPCM particle (m)
D_p	dimensionless diameter of MEPCM particle
Fo	Fourier number, $Fo = \frac{\alpha_m t}{L^2}$
G	gravitational acceleration ($m\ s^{-2}$)
h	heat transfer coefficient ($W/m^2\ K$)
h_{LS}	latent heat (J/kg)
k	thermal conductivity (W/m K)
K	permeability (m^2)
L	width of enclosure (m)
Q	accumulated energy (J)
Q^*	dimensionless accumulated energy
q''	heat flux (W/m^2)
Sb_c	subcooling parameter, $(T_M - T_c)/(T_h - T_M)$
Ste_m	Stefan number, $c_{p,m}\ (T_h - T_M)/h_{LS}$
X, X	dimensional and dimensionless dimensionless x coordinate
t	time (s)
T	temperature (°C)
$\forall$	volume (m^3)
α	thermal diffusivity (m^2/s)
$\bar{\xi}_L$	melting fraction of liquid phase
θ	dimensionless temperature, $(T - T_M)/(T_h - T_M)$
ρ	density (kg/m^3)
ε	porosity
τ_t	time delay

Subscripts

c	cold wall
e	effective
Exp.	experimental
f	qualtities for base fluid
fm	base fluid/mixture
fp	base fluid/PCM
h	hot wall
i	initial
L	liquid
M	melting point
m	effective quantities of porosity
mf	mixture/bas fluid
Num.	numerical
net	net
p	quantities for MEPCM
pf	MEPCM/bas fluid
pm	MEPCM/mixture

thermal storage in an enclosure filled with microencapsulated phase change materials (MEPCMs). This motivates the present study. The transient characteristics of thermal energy storage in an enclosure packed with MEPCM particles were investigated experimentally and numerically in this work.

2. Experimental Study

2.1. Experimental setup

The schematic of the experimental setup was shown in Fig. 1(a). The experimental test apparatus contains the test cell, resistive electrical heaters, insulation material, DC power supply, constant temperature bath, and the data acquisition system. The interior dimensions of the test cell were square cross section of 25×25 mm with 60 mm in depth. The two vertical walls of the enclosure were maintained at the constant temperatures, T_h and T_c, respectively. While the remaining side walls of enclosure were thermally insulated. The vertical hot and cold walls were made of copper plate, and the other walls of the test cell were fabricated from acrylic material. The hot wall was heated by an electrical foil heater made of flat strip Nichrome wires with feedback of the deviation of the hot wall temperature from the desired value to achieve the isothermal condition of hot wall. To reduce the heat loss from the hot wall, a compensative heater is installed parallel to the rear surface of the main heater to ensure negligible temperature gradient between the two heaters. The cold wall with flow channels circulated with temperature-controlled fluid from a thermostat (Lauda, RC20) was maintained at cold temperature. All the external surfaces of the test cell were insulated with Styrofoam insulation material of 40 mm thickness to minimize heat losses to the surroundings. Five T-type thermocouples were installed in the test cell at various locations to measure the transient temperature variations. Thermocouples were calibrated in a constant temperature bath with a mercury thermometer with a scale reading to 0.05 °C.

2.2. Properties of the MEPCM particles

In the present study, the microencapsulated phase change material (MEPCM) particles were purchased from Microtek Laboratories, Inc. with product number M-18C. The core PCM of MEPCM particles is n-octadecane with melting point of 24 °C, while their mean particle sizes are in the range of 15–25 μm. The thermophysical properties including density and thermal conductivity were measured as a function of temperature. Density was measured using a hydrometer (Tomei Co. Ltd., Japan) which has a measuring accuracy of within $\pm 5 \times 10^{-4}\ kg/m^3$. The thermal conductivity measurements were made by the Decagon devises KD2 thermal analyzer with a standard deviation of ±5%. Moreover, the melting/freezing temperatures and the latent-heat capacity of the MEPCM particles were analyzed by differential scanning calorimetry (DSC, Perkine Elmer DSC 7). The DSC measurements were performed with heating or cooling rates of 2, 5 and 8 K/min and temperature range of 12–40 °C. Comparisons of specific heat evolution with temperature during melting of the MEPCM before and after corrections of DSC curves are shown in Fig. 2 for different heating rates. An overall inspection of Fig. 2 discloses that the peak of specific heat increases with the decrease in the heating rate for both cases with or without correction. In addition, for the cases without correction, the peak is shifted to higher temperature for the case with a higher heating rate. A carful inspection of Fig. 2 discloses that at high heating rate of 8 K/min, the correction is significant. This s means that the direct utilization of specific heat evolution obtained from DSC measurements would cause an inaccurate representation of the phase change phenomena and incorrect results of mathematical modeling during design and optimization. The corrected specific heat evolutions with temperature during melting indicate that the corresponding temperatures of the corrected peak specific heat for different heat rates are almost the same.

Uncertainties in the measured quantities in this work were estimated to be ±0.3 °C in the temperature, ±5.0% in the thermal