Applied Energy 87 (2010) 620–628

Contents lists available at ScienceDirect

Applied Energy

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

Experimental assessment of heat storage properties and heat transfer characteristics of a phase change material slurry for air conditioning applications

Bogdan M. Diaconu [a,b,*], Szabolcs Varga [a], Armando C. Oliveira [a]

[a] New Energy Technologies Unit, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b] Faculty of Engineering, University "Constantin Brâncuşi", Tg-Jiu, Str. Republicii nr. 1, Tg-Jiu, Romania

ARTICLE INFO

Article history:
Received 26 August 2008
Received in revised form 30 April 2009
Accepted 3 May 2009
Available online 26 May 2009

Keywords:
Phase change material slurry
Enthalpy change
Natural heat transfer coefficient

ABSTRACT

A new microencapsulated phase change material slurry based on microencapsulated Rubitherm RT6 at high concentration (45% w/w) was tested. Some heat storage properties and heat transfer characteristics have been experimentally investigated in order to assess its suitability for the integration into a low temperature heat storage system for solar air conditioning applications. DSC tests were conducted to evaluate the cold storage capacity and phase change temperature range. A phase change interval of approximately 3 °C and a hysteresis behaviour of the enthalpy were identified. An experimental set-up was built in order to quantify the natural convection heat transfer occurring from a vertical helically coiled tube immersed in the phase change material slurry. First, tests were carried out using water in order to obtain natural convection heat transfer correlations. Then a comparison was conducted with the results obtained for the phase change material slurry. It was found that the values of the heat transfer coefficient for the phase change material slurry were higher than for water, under identical temperature conditions inside the phase change interval.

1. Introduction

Thermal energy storage is a relatively new technology with growing interest for a large number of thermal applications, including cooling in buildings. Systems using phase change materials (PCMs) are interesting due to the advantage of a high ratio between the amount of heat stored and temperature variation. Microencapsulated PCMs consisting of polymer shell capsules containing phase change material are used to enhance the surface area to volume ratio, thus improving the heat exchange performance in comparison with direct use of phase change materials. The phase change temperature range depends on the nature of the phase change material, which normally consists of a binary system of straight chain (normal) *n*-alkanes $CH_3–(CH_2)_n–CH_3$.

Implementation of heat storage systems based on microencapsulated PCMs poses a series of problems such as supercooling, chemical stability, increased pressure drop, limited heat transfer rate and complex thermophysical properties. Understanding the complex nature of the thermophysical properties and estimating the heat transfer characteristics are essential for an appropriate design.

The phase change temperature range and the enthalpy change are the key thermal properties of phase change slurries, since these parameters determine the heat storage capacity and their potential application. Compared to conventional fluids, phase change slurries exhibit high values of the apparent specific heat capacity during the phase change process that enhance the heat transfer rate between the fluid and the wall [1].

Only a few theoretical investigations have been carried out for modelling the phase change temperature range of binary mixtures. A summary of the available models can be found in He et al. [2]. In the same paper it was shown that for a given binary mixture of tetradecane and hexadecane, the phase change temperature range decreased as the mole percentage of tetradecane was either close to 0 or close to 1 (solution purity increased).

An important difficulty in modelling the heat storage properties of phase change material slurries is the hysteresis-like behaviour of the thermal properties. A typical PCM slurry has different values of enthalpy for the same temperature value, depending on whether the temperature value in question was reached by cooling or by heating. It is a complex phenomenon that depends mostly on supercooling effects. Other factors are the scanning rate and sample size. Little information is available in the literature. Lázaro et al. [3] reported supercooling data for a few PCMs. The values of temperature difference corresponding to the same value of enthalpy during heating and cooling inside the phase change temperature range are listed in Table 1.

---

[*] Corresponding author. Address: Faculty of Engineering, University "Constantin Brâncuşi", Tg-Jiu, Str. Republicii nr. 1, Tg-Jiu, Romania. Tel.: +40 722 913828; fax: +40 253 214462.

E-mail address: diaconu@utgjiu.ro (B.M. Diaconu).

0306-2619/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2009.05.002

Nomenclature

A	heat transfer surface area (m^2)
B	baseline of the DSC curve
c_p	specific heat capacity (J/(kg °C))
D	helix diameter (m)
d	tube diameter (m)
G	flow rate (kg/s)
H	specific enthalpy (J/kg)
h	heat transfer coefficient ($W/(m^2\ °C)$)
k	thermal conductivity (W/(m °C))
L	tube length (m)
LMTD	logarithmic mean temperature difference (°C)
m	DSC sample mass (kg)
Nu	Nusselt number, $Nu = hl/k$
Pr	Prandtl number, $Pr = \nu/\alpha$
Q	heat flow in the DSC sample (mW)
q	heat flow exchanged in the heat transfer system (W)
r	DSC scanning rate (°C/min)
Ra	Rayleigh number, $Ra = g\beta(t_w - t_b)\, L^3/(\nu\alpha)$
Re	Reynolds number, $\mathrm{Re} = wd/\nu$
S	differential signal recorded by the DSC
t	temperature (°C)
U	overall heat transfer coefficient ($W/(m^2\ °C)$)
w	velocity (m/s)
x	phase change progress parameter

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
τ	time (s)
ν	kinematic viscosity (m^2/s)

Subscripts

av	arithmetic average
b	bulk
e	external
end	end of phase change process
i	internal
in	inside
on	onset of phase change process
out	outside
w	wall
water	water

DSC analysis is the most widely used instrument in investigating the thermal properties of PCMs. However, DSC analysis only gives relative results and not absolute, depending on the scanning rate. Using a low scanning rate provides a better resolution, but on the other hand the influence of noise on the DSC signal increases. Arkar and Medved [4] investigated the thermal properties of RT20 paraffin by DSC measurements for a heating – cooling cycle at different scanning rates (5, 1 and 0.1 °C/min), identifying significant differences between the temperature values corresponding to the onset and end of the phase change process. Alvarado et al. [5] investigated methods of supercooling suppression of micro-encapsulated phase change materials. He et al. [6] investigated the thermal properties of a binary mixture $C_{14}H_{30}$ and $C_{16}H_{34}$ with 22% mole fraction of $C_{14}H_{30}$ using DSC. Three values of the scanning rate, 5, 2 and 0.5 °C/min were applied. Significant differences were found both in phase change characteristic temperatures (phase change onset and end temperatures) and the DSC profile. The DSC curve at a scanning rate of 0.5 °C/min resulted in two peaks instead of one peak like in the case of 5 and 2 °C/min. The phase change temperature range was significantly different in the three cases, showing a decrease with decreasing scanning rate. Yang et al. [7] investigated the thermal properties of four different slurry types with tetradecane as PCM and various shells. A significant influence of the shell material on the phase change characteristics (melting and freezing point, melting and freezing enthalpy) was reported. In addition, the super-cooling effect was present in all types of slurry.

Table 1
Supercooling magnitude and phase change temperature for a few PCMs, Lázaro et al. [3].

Material	Heating up–cooling down temperature shift (°C)	Phase change temperature (°C)
Gallium	2.5	29.8
Hexadecane	1.3	17.5
RT27	1.1	27
Sodium acetate trihydrate + graphite	2.0	59

Proper design of cold/heat storage applications with phase change slurries requires a good understanding of the heat transfer properties. Most studies available in the literature refer to forced convective heat transfer in tubes and micro-channels. Inaba et al. [8] described a numerical solution and an experimental validation procedure for the natural convection heat transfer occurring in a rectangular enclosure heated from below and cooled from above. A significant increase of the natural convection heat transfer coefficient during the phase change was found. It was explained by a larger value of the temperature difference between wall and the phase change slurry during the phase change process that increased the heat flow as compared to a fluid without phase change. It was also found that increasing the PCM mass concentration reduced the effect of heat transfer enhancement, due to the significant increase in viscosity. Taking into account both heat storage and heat transfer issues, Inaba's conclusions suggest the existence of an optimum value of PCM concentration. Inaba et al. [9] investigated natural convection heat transfer in rectangular enclosures filled with phase change slurry. Generalised correlations for the natural convection coefficient for three regions (PCM in solid phase, in phase change region and in liquid phase) were derived. An increase of the natural convection heat transfer coefficient up to 30% was predicted in comparison to a fluid without phase change, depending on the pseudoplasticity index of the fluid. Inaba et al. [10] conducted a numerical simulation of Rayleigh-Bénard convection of non-Newtonian phase-change-slurries in an enclosure with isothermal horizontal plates and adiabatic lateral walls. It was concluded that phase change slurries could enhance the natural convection heat transfer in enclosures up to 30%, compared to a fluid without phase change.

Zhang et al. [1] developed a theoretical model of forced convection heat transfer in laminar flow for a phase change slurry in a tube with constant wall temperature. The Stefan number and the concentration of PCM microcapsules were found to be the most important parameters influencing heat transfer. An increase of h as high as 4.5 times the value of a single phase fluid was calculated.

Alvarado [11] experimentally investigated the forced convection heat transfer of a phase change slurry (microencapsulated 99% *n*-tetradecane) under turbulent flow. In contrast to [8–10] it