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Research Paper

Experimental study on natural convective heat transfer of tube immersed in microencapsulated phase change material suspensions

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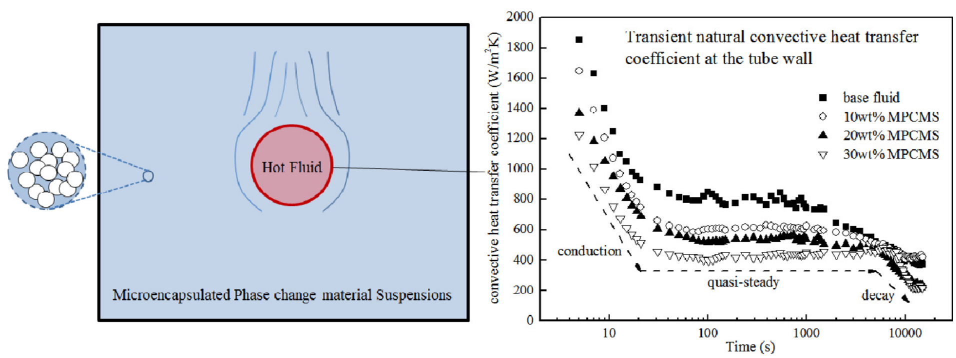
HIGHLIGHTS

- Synthesis stable suspensions with water–propanol mixture as the base fluid.
- Thermal properties of up to 30% mass fraction suspensions tested.
- Heat transfer coefficient decreases with increasing phase change material concentration.
- Temperature and flow rate of heat transfer fluid enhanced convective heat transfer.

GRAPHICAL ABSTRACT



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ABSTRACT

Microencapsulated phase change material suspensions have many potential applications in the fields of energy storage, air-conditioning and exchanger, etc. In this paper, stable microencapsulated phase change material suspensions are prepared with the water–propanol mixture as the base fluid and the addition of dispersants. The dependence of the specific heat, phase change enthalpy, rheological behavior and thermal conductivity of such fluids on the concentration and temperature is experimentally determined. And the heat storage and the natural convective heat transfer performance of tube immersed in the 10wt%–30wt% microencapsulated phase change material suspensions are experimentally studied. The result shows that the natural convection process can be characterized by three regimes: the pure conduction, the quasi-steady and the decay period. The convective heat transfer coefficient of a thick suspension is lower than the diluted one, although more heat can be stored by the thick suspension. And the increase of the temperature and flow rate of heat transfer fluid inside the tube is beneficial to the natural convective heat transfer performance.

1. Introduction

Nowadays more than 90% of global energy budget centers around heat conversion, transmission and utilization [1]. In order to balance energy demand and supply, improve the efficiency and reliability of energy systems, and reduce energy consumption and costs, thermal energy storage (TES) has been playing an important role in the whole energy chain during decades [1–3]. There are mainly three kinds of TES systems, namely sensible heat storage, latent heat

Abbreviations: DSC, differential scanning calorimetry; HTF, heat transfer fluid; min, minute; MPCM, microencapsulated phase change material; MPCMS, microencapsulated phase change material suspension; PCM, phase change material; SDS, sodium dodecyl sulfate; TES, thermal energy storage.

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storage and thermo-chemical storage. More attention has been paid to latent heat storage technologies due to its large energy density, stable input/output temperatures and other advantages [4–7].

As one of the phase change material (PCM) utilization forms, microencapsulated phase change material (MPCM) is the microsized particles composed of a PCM core coated with a thin polymer shell that holds the shape and prevent the PCM from leaking during the phase change period. The latent functionally thermal fluids formed by the MPCM particles suspending into the convectional heat transfer liquid have the advantages such as large area ratio, high energy density, small subcooling and small volume change during phase change process, and have shown superior performance as an enhanced heat transfer and thermal storage media [8–10]. Tyagi et al., Zhao and Zhang, Alkan et al., and Sarı et al. investigated and reviewed the fabrication, characterization and properties of the MPCM particles and suspensions respectively [11–14]. And many researchers conducted the forced convective heat transfer performance of MPCM suspensions in both circular tube [8,9] and rectangular tubes [10] by theoretical analysis, experiments and numerical simulations, and the MPCM shows superior heat transfer behavior because of the effect of phase change and micro-convection [14].

During the charging process, heat is transferred from heat exchanger to the TES material in the passive TES devices and vice versa during the discharging process. When MPCM suspensions were utilized as the passive TES material, the buoyancy driven natural convection characteristic of MPCM suspensions is the dominant factor that affects the heat charging/discharging rate and the heat storage performance. Inaba et al. and Zhang et al. studied the feather of Rayleigh–Bénard natural convection of the MPCM slurries by numerical simulation and experiment respectively [15,16]. They conducted the effect of mass concentration, the aspect ratio and the temperature on the natural convection heat transfer performance, and the result indicated that the phase change process of the MPCM will promote natural convection. Diaconu et al. experimentally investigated the natural convective heat transfer coefficient between the 45wt% MPCM slurry and the immersed vertical helically coiled tube, and the MPCM slurry displayed higher heat transfer coefficient than the water inside the phase change interval [17]. Allouche et al. conducted the natural convective heat transfer and cold storage characteristics of the 45wt% MPCM slurry heated/cooled by tube-bundle heat exchangers inside the tank, and found that the heat transfer coefficient increased during the phase change temperature range but remains smaller than water [18]. The above natural convective heat transfer research mainly concerned the steady R-B natural convection, and the unsteady natural convection of single concentration MPCM slurry around the helically coiled tube and tube-bundle heat exchangers, where the effect of related factors and the mechanism is not studied sufficiently.

In this study, the experimental study of the transient natural convective heat transfer of a tube immersed in microencapsulated phase change material suspensions (MPCMS) with the binary propanol–water mixtures as base fluid is performed. First, stable MPCMS with the MPCM mass fraction of 10wt%~30wt% is formulated and the thermal properties such as enthalpy variation, specific heat, rheological behavior, viscosity and thermal conductivity are measured. Then an experimental system is established to investigate the natural convective heat transfer characteristics of the MPCMS and the effect factors including heat transfer fluid (HTF) flow rate and the HTF inlet temperature are also studied.

2. Preparation and thermal properties

2.1. Preparation

As a heat transfer and storage fluid, having good uniformity and suspending stability is one of the most important requirements for

Table 1
Samples of MPCMS and their stability.

Samples	Water:propanol	Alginate	SDS	Stability (2 days)	Stability (7 days)
1	1:0.46	0.1%	0.1%	Unstable	Unstable
2	1:0.46	0.2%	0.1%	Stable	Unstable
3	1:0.46	0.4%	0.2%	Stable	Stable
4	1:0.50	0.4%	0.2%	Stable	Stable
5	1:0.40	0.4%	0.2%	Stable	Stable

MPCMS. In this paper, the MPCMSs are formulated with MPCM powder with N-hexadecane as the core material and a diameter range of 10~40 μm whose density is about 941 kg/m^3 and the water–propanol mixture as the base fluids. The different ratio of water to propanol of the base fluids has been tested to fit the density of MPCM by the experiments in our previous work [19]. And further the effects of dispersants such as sodium dodecyl sulfate (SDS) and alginate are studied. By comparisons of different samples in Table 1, the MPCMS with the mass ratio of water to propanol ranging from 1:0.5~1:0.4, with 0.2wt% SDS and 0.4wt% alginate, shows the best stability and can maintain stable for more than 7 days.

2.2. Phase change temperature and latent heat

By using a TA Q2000 differential scanning calorimeter (DSC), both the MPCM particles and the suspensions are measured. The data of MPCM particles indicate that during the endothermic period, solid–solid phase change with a small enthalpy takes place before it melts and the onset temperature of melt/solidify is 50.85 °C/58.11 °C, with a latent heat of 152.8 J/g. The DSC curves of the 10–30wt% MPCMSs are plotted in Fig. 1, and it shows that the latent heat increases almost linearly with the MPCM mass fraction.

2.3. Rheological behavior and viscosity

The high viscosity of the concentrated suspensions is the negative effect that influences the heat transfer and heat storage performance of the natural convective heat transfer fluids. In this study, the rheological behavior and viscosity of 10~30wt% MPCM suspensions are measured with the TA DHR-2 rheometer. Fig. 2 shows the relationship between viscosity and shear rate of 10–30wt% MPCMSs under a room temperature of 20 °C; it can be seen that 10wt% and 20wt% MPCMS behave as the Newtonian fluids and the 30wt% MPCMS shows the shear thinning non-Newtonian characteristic. Table 2 shows that at the same temperature of 20 °C at the high shear rate of 100 1/s, the viscosity increases exponentially with

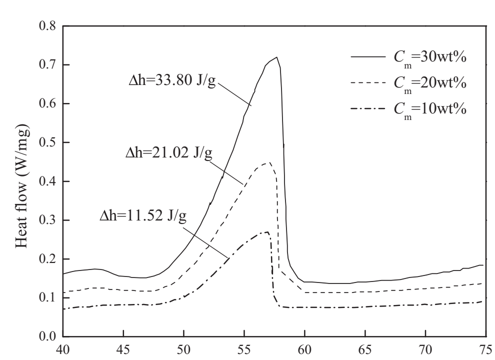

Fig. 1. DSC curve of 10–30wt% MPCMSs. DSC: differential scanning calorimeter, MPCMS: microencapsulated phase change material suspension.