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An experimental investigation of forced convection heat transfer with novel microencapsulated phase change material slurries in a circular tube under constant heat flux

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ABSTRACT

This paper proposes novel microencapsulated phase change material slurries (MPCSs) as both the energy storage media and heat transfer fluids. The flow and heat transfer characteristics of MPCSs have been experimentally investigated. A series of experiments were conducted in laminar, transition and turbulent flow conditions for MPCSs in a circular tube under constant heat flux, respectively. The results of pressure drop measurements showed that transportation costs of slurries were close to pure water. The heat transfer experiments demonstrated that proposed MPCSs could enhance the heat transfer performance as the heat transfer fluids for thermal system applications in comparison with pure water. The average enhancement percentages of the Nusselt number were 23.9%, 20.5% and 9.1% for MPCS of 5 wt%, and enhancement of the Nusselt number was achieved when phase change material in the microcapsules were in solid, solid/liquid and liquid states, respectively. However, heat transfer enhancement of MPCS depends on the following combination factors: the slurry concentration, the flow rate, the pumping power and the heating rate. Importantly, the phase change process must be carefully controlled in the heat transfer test section with above combination factors in order to take advantages of MPCS over pure water.

1. Introduction

Microencapsulated phase change material slurry (MPCS) can be employed as both the thermal energy storage media and heat transfer fluids, and thereby it has potential applications in the thermal energy storage and transportation systems [1,2]. Numerous researchers have made attempts to prove the benefits of MPCS in the thermal systems since the beginning of 1990s. The flow and heat transfer performance of MPCS attracted numerous researchers' attention due to their fundamental importance to the applications of MPCS. Consequently, a series of theoretical and experimental investigations on the flow and heat transfer performance of MPCS have been carried out by previous studies.

Charunyakorn et al. [3] proposed the governing equations for evaluating forced convection heat transfer behaviours of MPCS in an early study, and they claimed that the bulk *Ste* number and the concentration of slurry were the most important dominant parameters. They also indicated that particle size variation did not have a significant effect on the thermal performance of MPCS. Goel et al. [4] experimentally investigated a phase change material slurry with *n*-eicosane microcapsules in laminar forced convection heat transfer condition, and they indicated that the primary parameters were also the bulk *Ste* number and the volumetric concentration of slurry. However, they demonstrated that the volumetric concentration of slurry did not have a direct effect on the heat transfer behaviours of MPCS but it had an indirect effect. Zhang and Faghri [5] developed a numerical model for investigating laminar forced convection heat transfer performance of MPCS in a circular tube under constant heat flux by taking the effects of microcapsule's shell and initial supercooling into account, and they indicated that increased phase change temperature range could significantly reduce the heat transfer performance of MPCS in the tube. Roy and Avanic [6] also demonstrated that the shell of the microcapsule did not significantly affect the heat transfer behaviours of MPCS.

Yamagishi et al. [7] found that the heat transfer performance of MPCS was reduced in the laminar flow condition compared with the turbulent flow condition. Zhang et al. [8] carried out a theoretical analysis of convective heat transfer of MPCS in a circular tube under

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Nomenclature

$C_{p,eff}$	effective specific heat capacity (kJ/(kg·°C))
D	tube diameter (m)
f_D	Darcy friction factor
ΔH_c	heat of crystallization (kJ/kg)
ΔH_f	heat of fusion (kJ/kg)
h_x	local heat transfer coefficient (W/m^2·°C)
I	electrical current (A)
k	thermal conductivity (W/m·°C)
L	length (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure drop (Pa)
q_w''	wall heat flux (W/m^2)
Q	heating rate (W)
R	tube radius (m)
T	temperature (°C)
T_c	crystallizing temperature (°C)
T_m	melting temperature (°C)
u	flow velocity (m/s)
U	electrical voltage (V)
V	volume fraction (%)
W	mass fraction (–)
x	coordinate in the axial direction (m)

Greek letters

ρ	density (kg/m^3)
μ	viscosity (Pa·s)
ν	mean flow velocity (m/s)

Subscripts

b	bulk
i	inside/inlet
o	outside
p	particle
w	internal wall surface, water
wo	external wall surface
x	at axial position x

Dimensionless numbers

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

constant heat flux, and they introduced an improved *Nu* number to investigate laminar flow of MPCS in the tube and demonstrated that the heat transfer performance of MPCS could be enhanced by the phase change process. Inaba et al. [9] demonstrated that the average heat transfer coefficients of MPCS were about 2–2.8 times greater than that of pure water in both laminar and turbulent flow conditions via an experimental investigation. Wang et al. [10] also experimentally investigated the flow and forced convective heat transfer behaviours of MPCS in both laminar and low turbulent flow conditions. The effects of the pressure drop, local heat transfer coefficients, mass fractions of microcapsule, heating rates and flow rates on the heat transfer performance of MPCS were investigated, respectively. Other related numerical and experimental studies of flow and heat transfer characteristics of MPCS were carried out by Zhao et al. [11], Zeng et al. [12], Wang and Niu [13], Zhang et al. [14].

Several recent studies also attempted to investigate the flow and heat transfer behaviours of MPCS in the thermal systems. Wang et al. [15] demonstrated that MPCS with 2% microcapsules would increase *Nu* number 1.36 times compared with pure water. Li et al. [16] experimentally investigated the flow resistance characteristics a novel MPCS in a circular tube for engine cooling system, and they claimed that the thermal conductivity of composite microcapsules was enhanced by mixing graphene into the shell. They also reported that pumping consumption could be saved by MPCS compared with pure water. Liu et al. [17] proposed a novel MPCS to improve the thermal and electrical efficiencies of photovoltaic–thermal solar collectors, and they claimed that the overall net efficiency of the system with MPCS achieved 80.57% at 11:00 am and it was about 1.8% higher than the conventional water type. Liu et al. [18] also employed MPCS to improve the thermal and electrical performance of a compound parabolic concentrating photovoltaic/thermal collector, and the numerical results showed that the maximum thermal efficiency of the system was enhanced by 9.24% and the maximum electrical efficiency of the system was enhanced by 1.8% with application of MPCS in the system.

According to above literature review, the flow and heat transfer characteristics of MPCS depend on the following parameters: the heating rate of the test section, the flow rate of the slurry, the slurry concentration, the heat transfer coefficient, the Nusselt number, the Reynolds number, the homogeneous degree of the slurry, the supercooling degree, the phase change temperature range, and the particle size distribution. However, the influence directions of these parameters are known, but the degree of influences are still limited and not well understand. There is a lack of experimental investigations to enhance the existing studies and fully understand the benefits of MPCS. Therefore, the aim of this paper was to design and build a test rig to investigate the effects of some above parameters on the flow and heat transfer characteristics of two novel MPCSs in a circular tube under constant heat flux, and the degree of heat transfer enhancement was investigated as well. In this work, two novel types of MPCSs with microcapsule concentrations of 5 wt% and 10 wt% were fabricated with commercial microencapsulated paraffin mixtures and pure water. A series of experiments were conducted in laminar (Re < 2300), transition (2000 < Re < 4000) and turbulent flow (Re > 4000) conditions for prepared MPCSs, and the experiments were designed to cover all three flow conditions for investigating the heat transfer performance of MPCSs. This paper will provide useful guidance for practical engineering design of thermal energy storage systems with MPCS applications. In addition, thermo-physical and rheological properties of microencapsulated phase change materials (MPCMs) and microencapsulated phase change material slurries were also investigated.

2. Thermal and physical properties

2.1. MPCM properties

Microencapsulated phase change material (MPCM) – DS5001X is supplied by the BASF Group, Germany. The microcapsules comprise of paraffin mixtures core and highly crosslinked poly (methyl methacrylate) (PMMA) shell.

The surface morphologies of the microcapsules were investigated using an environmental scanning electron microscope (ESEM, Philips XL30). The sample was gold coated before the measurement. Fig. 1 shows a SEM image of the microcapsules, it can be seen that most of microcapsules present regular spherical shape and smooth surface structure. There are dents appear on the surface of the microcapsules, and this phenomenon can be attributed to the contraction which was caused by the crystallization of phase change materials (PCMs).