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Flow and heat transfer characteristics of phase change emulsions in a circular tube: Part 1. Laminar flow

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ABSTRACT

The flow and heat transfer characteristics of phase change emulsions (PCEs) in a circular tube have been investigated. The PCEs were heated under constant heat flux. The wall heat flux and mass fraction of the dispersed phase change material (PCM) particles were varied as experimental parameters. The PCEs showed Newtonian fluid behavior when the PCM mass fraction was less than 20 mass%. When the PCM mass fraction was 30 mass%, the PCE showed pseudoplastic fluid behavior. The Nusselt number of the PCEs is higher than that of the single-phase fluid because of latent heat absorption accompanying melting of the PCM particles. The heat transfer characteristics of the PCEs for melting PCM particles were also investigated using a numerical model, and the results were compared with the experimental results. The numerical results approximately agree with the experimental results when the PCM mass fraction is 20 or 30 mass%.

1. Introduction

Thermal fluids that store and transport thermal energy are used in thermal storage systems with a focus on decreasing environmental loading. Thermal fluids can be classified into two groups: sensible heat type and latent heat type fluids [1]. In recent years, latent heat type thermal fluids, such phase change slurries (PCSs) [2], dispersed in phase change material (PCM) particles have attracted more attention than sensible heat type fluids because they provide not only high density thermal energy storage by using the latent heat of the PCM particles but they also show good heat transportation. Ice slurries [3,4], clathrate hydrate slurries [5,6], and microencapsulated PCM slurries [7,8] are common PCSs. They are highly functional thermal fluids and have practical uses. However, they have problems, such as tube jams, caused by inhomogeneity of the flow state induced by sedimentation or the buoyancy force of PCM particles [9,10]. The inhomogeneous flow state can be prevented by fabricating microencapsulated PCM slurries with very small particles, but PCM encapsulation requires specialized equipment and the capsule can be thermally resistant. To overcome these problems, phase change emulsions (PCEs) have attracted increasing attention. A PCE is a mixture of a PCM and an aqueous solution. The PCM is dispersed as fine particles inside the aqueous solution. They are mixed by the action of a surfactant. The PCM particles inside PCEs are much smaller than those of PCSs. Thus, PCEs maintain a homogeneous state for a long time. Furthermore, the surfactant molecules around the PCM particles are very small and thus not thermally resistant. For these reasons, PCEs have attracted considerable interest.

The thermophysical properties of PCEs have been extensively investigated [11–13]. Huang et al. [11] investigated the heat capacity of PCEs. They found that PCEs show high heat capacity because of the latent heat of the PCM particles. Chen et al. [12] measured the thermal conductivity and latent heat of PCEs. They found that the thermal conductivity of PCEs depends on the dispersed PCM state. Furthermore, the latent heat of PCEs can be estimated from the latent heat of the PCM and its content. Huang et al. [14] and Chen et al. [15] investigated the flow characteristics of PCEs, and they reported different results. Huang et al. [14] found that PCEs show pseudoplastic fluid behaviour independent of the mass fraction of the dispersed PCM. Chen et al. [15] found that a PCE with 30 mass% PCM shows Newtonian fluid behaviour. The rheological behaviour of PCEs is complicated because there is an interaction between the dispersed particles, and further investigation is required. These studies suggest that PCEs can potentially be used as thermal media. To use PCEs as thermal media, their heat transfer characteristics must be known. Roy et al. [16], Choi et al. [17], and Saarinen et al. [18] investigated the heat transfer characteristics of PCEs. Roy et al. [16] investigated the heat transfer characteristics of PCEs for laminar flow, whereas Choi et al. [17] and Saarinen et al.

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Nomenclature

c	specific heat
D	inner tube diameter
Gz	Graetz number
h	heat transfer coefficient
I	electric current
k	thermal conductivity
l	latent heat
L	length
n	repetition times
Nu	Nusselt number
q	heat flux
T	temperature
u	velocity
U	electric voltage
x, r	location

Greek letters

ΔP	pressure drop
ϕ	fraction
$\dot{\gamma}$	shear rate
ρ	density

Subscripts

app	apparent
b	bulk mean temperature
cal	calculated value
d	dispersed phase
f	continuous phase
heat	heating section
in	inlet
lam	Nusselt number for laminar flow calculated by Eq. (10)
m	mean value
mass	mass
mep	melting end point
melt	melting point
msp	melting start point
out	outlet
p	phase change emulsion
test	test section
v	volume
w	wall
x	local

[18] investigated them for turbulent flow. Roy et al. [16] reported that the dimensionless temperature of PCEs is suppressed comparing with water because of latent heat absorption of melting of PCM particles. However, the effects of the mass fraction of the PCM, wall heat flux, and conditions of the PCM particles on the heat transfer characteristics have not been sufficiently investigated.

In present study, we prepared PCEs by D-phase emulsification and then investigated their flow and heat transfer characteristics for laminar flow inside a circular tube. D-phase emulsification is a type of chemical emulsification and it has attracted attention because it provides an emulsion that is stable and thermally durable [12,19,20]. Two paraffin-based PCMs, *n*-hexadecane (melting point 17.5 °C) and *n*-octadecane (melting point 27.2 °C), were used as the dispersed phase of the PCEs. The mass fraction of the PCM, its state (solid, liquid, or melting), and the wall heat flux were chosen as experimental parameters. The heat transfer characteristics were also investigated by solving an energy equation applying the finite differential method. The effect of latent heat absorption associated with melting was treated as the increase of the apparent specific heat of the PCE.

2. Emulsion generation procedure and the properties of the PCEs

2.1. Procedure

We used D-phase emulsification to generate the PCEs. D-phase emulsification was performed as follows. An alcohol (1,3-butandiol, Wako, 2 g), water (2 g), and a surfactant (polyoxyethylene (20) sorbitan monooleate, Wako, 4 g) were mixed to give a mixture called the D-phase. Liquid oil (*n*-hexadecane or *n*-octadecene, Wako, 10 g) as a PCM was slowly added to the D-phase, and the mixture was stirred until an oil-in-D-phase (O/D) gel emulsion formed. The O/D gel emulsion was then diluted with water (82 g) and the mixture was stirred, forming 100 g of an oil-in-water (O/W) emulsion containing 10 mass% PCM. The O/D gel had a water:alcohol:surfactant:PCM mass ratio of 1:1:2:5. PCEs with 10, 20, and 30 mass% PCM were generated by changing the amount of dilution water.

2.2. Properties of the PCEs

The properties of PCEs with solid and liquid PCM particles are given in Table 1. Based on previous work [19], the density, specific heat, and latent heat of the PCEs were estimated from the properties and compositions of the PCEs. The thermal conductivity of the PCEs was estimated by Maxwell's equation:

$$k_{\mathrm{p}} = k_{\mathrm{f}}\left[\frac{2k_{\mathrm{f}} + k_{\mathrm{d}} + 2\varphi_{\mathrm{v}}/100(k_{\mathrm{d}} - k_{\mathrm{f}})}{2k_{\mathrm{f}} + k_{\mathrm{d}} + \varphi_{\mathrm{v}}/100(k_{\mathrm{f}} - k_{\mathrm{d}})}\right], \tag{1}$$

where k_{f} and k_{d} are the thermal conductivities of the continuous and dispersed phases, respectively, and ϕ_{v} is the volume fraction of the PCM inside the PCE. The melting point of the PCE was determined from the temperature history of the PCE heated using a calorimeter.

Fig. 1 shows the particle size distributions of the PCEs. The distributions were measured using a laser diffraction particle size analyzer (SZ-100 nanoparticle analyzer, Horiba). As shown in Fig. 1, the distributions are similar for all of the PCEs despite their different PCM types and mass fractions. The most frequent particle diameter is about 200 nm.

3. Experimental apparatus and procedure

3.1. Experimental apparatus

Fig. 2 shows a schematic diagram of the experimental apparatus used to evaluate the flow and heat transfer characteristics of the PCEs. The apparatus consists of inlet and outlet reservoirs, a thermostatic bath, a gear pump, an entrance region to obtain developed flow, a test section to measure the heat transfer coefficient and pressure drop, a differential manometer, a power supply, a flow meter, an outlet reservoir, and associated instruments. A thermostatic bath was used to cool the PCE and maintain the prescribed PCE temperature. The entrance region and test section consist of a stainless tube with diameter and length of 7.5 mm and 1.0 m, respectively. The differential manometer is connected to both ends of the test section to enable the pressure drop of the fluid that flows through the test section to be measured. Fig. 3 shows the details of the test section. A nichrome foil heater