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Flow and heat transfer characteristics of phase change emulsions in a circular tube: Part 2. Turbulent flow

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ABSTRACT

Phase change emulsion (PCE) has recently attracted attention as a thermal media in thermal energy storage systems because it has the advantages of high-density thermal storage and transportability. In the present study, the heat transfer characteristics of a phase change emulsion (PCE) for turbulent flow were experimentally investigated. Wall heat flux, mass fraction of PCM, and Reynolds number were the varied experimental parameters. For turbulent flow, it was found that the Nusselt number of the PCE with melting dispersed PCM particles was higher than that of a single-phase fluid. The Nusselt number varied along the flow direction and the maximum Nusselt number was about 2.2 times higher than that of a single-phase fluid. Furthermore, the increasing ratio depended on the wall heat flux and the latent heat held by the PCE. However, the Reynolds number had little influence on the ratio. A modified Stefan number was defined and an equation that represents the melting heat transfer characteristics of a PCE in a turbulent flow region was derived using the modified Stefan number, Reynolds number, and Prandtl number.

1. Introduction

Phase change slurries (PCSs), which are a mixture of small phase change material (PCM) particles and an aqueous solution, have been used as carrier fluids in thermal energy storage systems for their efficient utilization of thermal energy [1–4]. The latent heat of dispersed PCM particles provides high-density thermal storage and good heat exchange performance. Recently, phase change emulsion (PCE) has attracted attention as a PCS [5]. PCE is a mixture of water and PCM, which are mixed by the action of a surfactant. The emulsions are generally classified as oil-in-water (O/W) or water-in-oil (W/O). PCE is an O/W type emulsion and the PCM is dispersed inside the water. The particle size in PCEs is generally smaller than in other PCSs [6]. Because of the smallness of the PCM particles, they are homogeneously dispersed inside the water and remain homogeneous for an extended period of time. In practical systems using PCSs, pipe blockages are caused by heterogeneous dispersion of particles and adherence of the particles to the cooling surface. Using PCEs can solve these problems, because the PCM particles inside the PCE are homogeneous even during flow. Furthermore, dispersed PCM can be changed corresponding to a target temperature range. Therefore, PCE has potential as a thermal storage and transportation fluid [7,8].

The thermophysical properties and flow characteristics of PCEs have been widely studied. Zhang et al. [9] studied key factors affecting the thermophysical properties, stability, and viscosity of PCEs, and reported that the surfactant and emulsification played an important role in these properties. Morimoto et al. [10], Kawanami et al. [11], and Chen et al. [12] studied the thermophysical properties of a PCE prepared by D-phase emulsification. Furthermore, they investigated the flow characteristics of the PCE. Chen et al. [13] studied the flow characteristics of a PCE inside a circular tube and reported that the PCE with 30% PCM by mass exhibited Newtonian fluid behaviour. However, Morimoto et al. and Chen et al. reported that the PCE showed pseudoplastic fluid behaviour when the PCM mass fraction was 40%. Furthermore, Huang et al. [14] reported that a PCE with 10–75% PCM by mass showed pseudoplastic fluid behaviour.

To design thermal energy storage systems, the heat transfer characteristics of PCEs must be known. Choi et al. [15], Roy et al. [16], and Saarinen et al. [17] studied the heat transfer characteristics of PCEs. Choi et al. and Saarinen et al. studied the heat transfer characteristics for turbulent flow. Choi et al. reported the heat transfer coefficient of a PCE in a circular tube varied along the flow direction and was higher than that of a single-phase fluid when PCM particles were melted. Saarinen et al. reported the PCE showed heat transfer enhancement at a Reynolds number greater than 7000. However, the main factors affecting the heat transfer characteristics have not been clarified. Furthermore, the effect of

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Nomenclature

c	specific heat [J/(kg·°C)]
C	heat capacity [J/kg]
D	inner tube diameter [m]
h	heat transfer coefficient [W/(m^2·°C)]
I	electric current [A]
k	thermal conductivity [W/(m·°C)]
l	latent heat [J/kg]
L	length [m]
m	mass [kg]
n	number of repetitions [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
q	heat flux [W/m^2]
Q	applied heat [J]
Re	Reynolds number [–]
Ste	Stefan number [–]
T	temperature [°C]
u	velocity [m/s]
U	electric voltage [V]
x	location [m]
y	thickness of viscous sublayer [m]

Greek symbols

ϕ	fraction [%]
μ	viscosity [Pa·s]
λ	friction factor [–]
ρ	density [kg/m^3]
τ	shear stress [Pa]

Subscripts

app	apparent viscosity
b	bulk mean temperature
cal	calculated value
d	dispersed phase
emp	empirical value
exp	experimental value
f	continuous phase
fin	final temperature of latent heat measurement
heat	heating section
i	initial temperature of latent heat measurement
in	inlet
liq	liquid phase
m	mean value
mass	mass fraction
max	maximum value
melt	melting point
mod	modified
out	outlet
PCE	phase change emulsion
sol	solid phase
t	total
w	wall
water	water
x	local

the latent heat held by the PCE has not been studied. The latent heat is important for heat transfer enhancement because it is attributed to the specific heat enhancement of the PCE associated with latent heat absorption.

In this study, the heat transfer characteristics of a PCE for turbulent flow were experimentally investigated and estimation of the latent heat held by the PCE at various parts of the circular tube, which was difficult with the measurement in the laminar flow region of Part 1 [18], was carried out by measuring the latent heat, and the modified Stephan number was introduced. Furthermore, effects of a wall heat flux and the Reynolds number on the heat transfer characteristics were investigated. The PCE was prepared by D-phase emulsification and *n*-hexadecane was used as the PCM.

2. Generating procedure and properties of the PCE

2.1. Procedure

We used D-phase emulsification to generate the PCE. Alcohol (1,3-butandiol, Wako, 2 g), water (2 g), and a surfactant (polyoxyethylene (20) sorbitan monooleate, Wako, 4 g) were mixed to produce the D-phase. Liquid oil (*n*-hexadecane, Wako, 10 g) used as the 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% PCM by mass. The O/D gel had a water:alcohol:surfactant:PCM mass ratio of 1:1:2:5. PCEs with 10% and 15% PCM by mass were generated by changing the amount of dilution water.

2.2. Properties of the PCE

Table 1 shows the properties of the PCEs with solid and liquid PCM particles. Based on our previous work [10], the density, specific heat, and latent heat of the PCE were estimated from properties and content rate of its composition. The apparent viscosity $\mu_{\rm app}$ [Pa·s] of the PCE was obtained from the relationship between the wall shear stress and shear rate of PCEs, because the PCE used in the present study showed Newtonian fluid behaviour [10,12]. The thermal conductivity of the PCE was estimated using Maxwell's equation as follows:

$$k_{\rm PCE} = k_{\rm f}\left[\frac{2k_{\rm f} + k_{\rm d} + 2\phi_{\rm v}/100(k_{\rm d} - k_{\rm f})}{2k_{\rm f} + k_{\rm d} + \phi_{\rm v}/100(k_{\rm f} - k_{\rm d})}\right] \tag{1}$$

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

Fig. 1 shows the particle size distribution of PCEs used in the present study. The distribution was measured using a laser diffraction particle size analyzer (SZ-100 nanoparticle analyzer, Horiba). When the D-phase emulsification was applied, the PCEs showed

Table 1
Physical properties of the PCEs.

Test sample		PCM: n-hexadecane	
		10 mass%	15 mass%
Specific heat	Solid phase	4.0	3.8
$c_{\rm PCE}$ [kJ/(kg·°C)]	Liquid phase	4.0	3.9
Density	Solid phase	986.4	986.0
$\rho_{\rm PCE}$ [kg/m^3]	Liquid phase	978.5	980.9
Thermal conductivity	Solid phase	0.56	0.54
$k_{\rm PCE}$ [W/(m·°C)]	Liquid phase	0.54	0.49
Apparent viscosity	Solid phase (12 °C)	2.9	4.9
$\mu_{\rm app}$ [mPa·s]	Liquid phase (30 °C)	1.7	3.0
Latent heat	$l_{\rm PCE}$ [kJ/kg]	22.9	34.4
Melting point	$T_{\rm melt}$ [°C]	17.5	