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Thermal–hydraulic characteristics of ethylene glycol aqueous solutions containing microencapsulated paraffin

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A R T I C L E I N F O

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A B S T R A C T

The study involved investigating heat exchange performance with a microcapsule – ethylene glycol/water slurry for flow in a horizontal circular tube under constant heat flux boundary conditions. The microcapsule included paraffin as a phase change material and was 250 μm in average diameter. The particle fraction in the slurry corresponded to 15 wt%. Measurements were performed for both cases with or without the phase change. The friction factor of the microcapsule slurry obtained by pressure drop measurements increase when compared with ethylene glycol/water, and this indicated increase in flow resistance. Interestingly, the heat exchange output of the microcapsule slurry at 10 wt% increased by up to 10% compared to that of the ethylene glycol/water solution under the same pressure drop conditions. This is due to the reduction in the boundary-layer thickness given the effect of particle agitation and the increase in heat capacity with latent heat. The heat exchange output of the microcapsule slurry under the same pressure-drop conditions decreased for a particle concentration exceeding 10 wt%, and this resulted from the increase in the negative effect of the flow resistance.

1. Introduction

In the last decade, energy consumption has significantly increased with economic and population growth in developing countries. Highly efficient application of energy is essential for global environmental conservation and sustainable human development. However, the present efficiency of energy use is low and consequently approximately 70% of energy is discarded as waste heat. The thermal management that consists of thermal conversion, storage, and transportation is one of the most important agendas to enable the utilization of thermal energy.

The present study focused on the transportation of thermal energy. Ethylene glycol and silicone oil are generally known as mediums of heat transportation, and their transport capacity is limited [1,2]. Phase change materials (hereafter referred to as PCMs) receive significant attention as thermal storage/control materials; this is because a high amount of heat is absorbed and released isothermally during the phase change processes. Recently, a few organic and inorganic PCM candidates were investigated as materials for latent heat storage [3–7]. Among the materials, paraffins are typically known since their energy storage density is high. It is possible to control the melting temperature through the number of carbon atoms in their chains. However, most paraffins are associated with large volume changes when phase change occurs. Additionally, the addition of the micron sized particles in base fluids leads to a few practical problems such as the blockage and erosion of a pipeline followed by an increase in pumping power. And what is worse, as a potential method for enhancing heat transfer coefficients, multiphase flow in which micron-sized solid particles (for example, metal) are dispersed in a base fluid, such as water and ethylene glycol, was initially proposed and examined. In this case, the thermal conductivity of the multiphase fluid is enhanced when compared with that of the base fluid and results in higher heat transfer coefficients. Additionally, the enhancement in the convective heat transfer is attributed to the effect of agitation and the impinging jet due to the inertia between the base fluid and the solid particle that attenuates the thermal boundary layer [8].

As mentioned previously, it is important for the heat transfer in PCM slurries to prevent the blockage of a pipeline due to the agglomeration of PCMs and large volume changes during phase change process. In order to solve the above problems, microencapsulation of the PCM is an extremely effective approach. The microencapsulated PCM (hereafter referred to as MCPCM) enhances the heat exchange output between the fluid and the heat transfer surface due to the following functions: the hold of temperature difference (i.e., driving force of heat transfer) due to the latent heat effect, and the reduction in the boundary-layer thickness due to the effect of interaction between particles and tube wall [9,10]. However, microencapsulation generally reduces PCM's

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Nomenclatures

Variables

A	surface area of the test section, m^2
B	shape parameter
C_p	specific heat, J/(gK)
d	diameter of a particle, m
D	diameter of a tube, m
f	friction factor
F	volumetric flow rate, m^3/s
h	heat transfer coefficient, $W/(m^2\ K)$
H_m	latent heat, kJ/kg
L	length of the test section, m
Nu	Nusselt number
P	pressure, Pa
Pr	Prantl number
Q	heat exchange output, W
Re	Reynolds number
T	temperature, K
u	flow rate, m/s
w	weight fraction
X	horizontal coordinate
α	PCM inclusion ratio in MCPCM (based on weight)
ε	roughness degree
ϕ	volume fraction
μ	viscosity, Pa•s
λ	thermal conductivity, W/(mK)
ρ	density, kg/m^3

Subscripts

app	apparent
ave	average
c	core
EG	ethylene glycol aqueous solution
i	inside wall
in	inlet
m	melt
p	particle
o	outside wall
out	outlet
s	slurry
sh	shell
w	wall

reactivity and thermal conductivity due to the separation of shell materials from environment, and thus it is necessary to select appropriate shell materials with a desired shell thickness. Extant studies reported MCPCMs with some shell materials including polyurea [11], gelatin/acacia [12], silica [13], melamine-formaldehyde [14,15], and Polymethyl methacrylate (PMMA) [16,17] and also examined their thermal-flow properties [18,19].

The present study focused on enhancing the efficiency of coolants for vehicles. We selected paraffin with a melting point of approximately 353 K as a PCM that is closed to the exhaust heat from the automotive engines. In the present study, the PCM was microencapsulated by means of a general coacervation method. Subsequently, thermophysical properties of the MCPCM were measured. Additionally, the heat transfer coefficients and friction factor with the MCPCM – ethylene glycol/water slurry (hereafter referred to as the MCPCM slurry) were determined for the flow in a horizontal circular tube under constant heat flux boundary conditions. The particle fraction of the MCPCM in the slurry ranged from 5 to 15 wt%. The experiments were performed under turbulent conditions of the Reynolds number ranging from 3000 to 20,000 and performed in both cases with or without the phase change of the MCPCM. The slurry temperature in the entrance of the test section was maintained at 353 K. The dependencies of the heat exchange output and flow resistance on the particle fraction in the slurry were evaluated under constant heat flux boundary conditions. Finally, the feasibility of the slurry containing the MCPCM as a new medium for coolant was briefly discussed.

2. Experimental section

2.1. Materials

The paraffin as PCM was obtained from Rubitherm Technology GmbH. and corresponded to the mixed paraffin termed as Rubitherm®RT90HC. The microencapsulation of the PCM was performed through phase separation based on the coacervation method [20] in Japan Capsular Products, Inc. Fig. 1 shows the micrograph of the dry MCPCM particles. The average diameter of the MCPCMs was 250 μm. The thermophysical properties including melting point, supercooling degree, and latent heat amount were measured by using a Thermo Gravimetry Analyzer (Thermoplus TG-8120, Rigaku) and a Differential Scanning Calorimeter (DSC Q1000, TA Instruments). Additionally, other thermophysical properties were calculated by using the following equations [18,21]:

$$\rho_p = (1/\alpha)\cdot(d_c/d_p)^3\cdot\rho_c \tag{1}$$

$$C_{p,p} = \{\alpha C_{p,c} + (1-\alpha)C_{p,sh}\}\rho_c\rho_{sh}/[\{(1-\alpha)\rho_c + \alpha\rho_{sh}\}\rho_p] \tag{2}$$

$$1/(\lambda_p d_p) = 1/(\lambda_c d_c) + (d_p-d_c)/(\lambda_{sh} d_p d_c) \tag{3}$$

The properties of the MCPCM are listed in Table 1. Ethylene glycol (hereafter referred to as EG) with 99.5% purity was obtained from Wako Pure Chemical Industries Ltd. All the materials were used without further purification. Deionized water was produced by using water-manufacturing equipment (G-5C BB-5A) manufactured by Organo Co. In the present study, the dispersion medium corresponded to EG aqueous solution in which the weight fraction of EG was 50% (50 wt%). The thermophysical property of the EG aqueous solution is listed in the reference report [22].

2.2. Experimental apparatus

A schematic illustration of the experimental apparatus is shown in

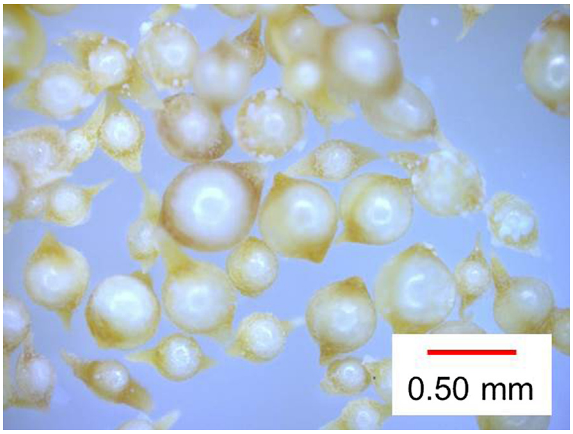

Fig. 1. Micrograph of the dry MCPCM particles.