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Melting Heat Transfer Characteristics of Plural Phase Change Microcapsules Slurry Having Different Diameters

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Abstract : The present study has been performed for obtaining the melting heat transfer enhancement characteristics of water mixture slurries of plural microcapsules having different diameters encapsulated with solid-liquid phase change material(PCM) flowing in a pipe heated under a constant wall heat flux condition. In the turbulent flow region, the friction factor of the present PCM slurry was to be lower than that of only water flow due to the drag reducing effect of the PCM slurry. The heat transfer coefficient of the PCM slurry flow in the pipe was increased by both effects of latent heat involved in phase change process and microconvection around plural microcapsules with different diameters. The experimental results revealed that the average heat transfer coefficient of the PCM slurry flow was about 2~2.8 times greater than that of a single phase of water.

Key words : Melting Heat Transfer, Phase Change Material, Plural Microcapsules, Microconvection

Nomenclature

B = drag force of sphere, Pa
C = mass concentration of PCM particle
C_B = drag coefficient of sphere
C_{big} = mass concentration of PCM particle with large size according to small size PCM slurry which has no phase change in this experimental temperature range
C_{sma} = mass concentration of PCM particle with small size which has phase change in this experimental temperature range
C_z = lift coefficient of sphere
C_p = specific heat, kJ/(kg · K)
D = tube diameter, m
DR = drag force ratio as defined in Eq. (18)
d = diameter of microcapsule, m
f = friction factor

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g = gravitational acceleration, m/s^2
HTR = nondimensional heat transfer ratio as defined in Eq. (18)
h = heat transfer coefficient, W/(m^2 · K)
j_H = nondimensional heat transfer parameter
k = thermal conductivity, W/(m · k)
L = latent heat of PCM, kJ/kg
l = length, m
m = mass flow rate, kg/s
n = index
Nu = Nusselt number
P = pressure, Pa
Pr = Prandtl number
Pr' = modified Prandtl number based on power law as defined in Eq. (8)
q = heat flux, W/m^2
Q = quantity of heat, W
R = tube radius, m
r = radial distance, m
Re = Reynolds number
Re' = modified Reynolds number based on power law as defined in Eq. (8)
S = projective surface area of sphere, m^2
St = Stanton number
Ste = Stefan number
T = temperature, K
t = time, s
U = velocity, m/s
V = volume, m^3
x = axial distance, m
Z = lift force of sphere, Pa
Δ = difference

Greek Symbols

μ = viscosity, kg/(m · s^n)
ρ = density, kg/m^3
χ = nondimensional axial distance
ω = angular velocity of sphere, s^{-1}

Subscripts

ave = average
b = bulk
big = microcapsule particle with relatively large diameter
e = entrance region
hw = heating wall
hx = local position on the heating wall in x direction
m = melting point
nf = Newtonian fluid
p = particle
r = radial direction
sma = microcapsule particle with relatively small diameter
te = test section
th = theoretical
tot = total
tr = transfer
w = water
x = axial direction
$x0$ = center of tube

1. Introduction

The use of microencapsulated phase change material slurry has been widely spread in practice since a couple of decades because of high energy storage density owing to latent heat generation during a phase change process[1].

Especially, the possibility of PCM slurry transportation in a pipe was discussed by Mehalick and Tweedie[2]. Kasza and Chen[3] elucidated that the heat transfer coefficient of microencapsulated phase change suspension flow could be increased as much as three times than that of only water flow in a pipe. Hart and Thornton[4] reported a two-fold increase in the effective specific heat of suspension and showed that the PCM microcapsules ranging of 5-50 μm in diameter could be pumped without destroying microcapsule's shell. The heat transfer characteristics of PCM slurry flow in circular ducts were clarified by the numerical solutions, Charunyakorn et al[5]. They showed that the obtained heat fluxes, which were about 2~4 times higher than a single phase flow, might be achieved by the PCM slurry flow. The physical mechanism of the convection heat transfer enhancement due to the PCM particles was provided in the PCM slurry turbulent flow in a pipe[6]. The melting and solidification heat transfer characteristics of PCM slurry flowing in a heat transfer pipe were examined experimentally and numerically for the uniform size of microcapsules[7].

The purpose of the present study is to examine heat transfer characteristics of microconvection in the PCM slurry composed of plural microcapsules with different diameters as well as latent heat of PCM particles in phase change process. In other words, this paper tried to clarify the heat transfer enhancement effect of microconvection by adding large size microcapsule particles to the uniform PCM slurry having small size microcapsule particles. Especially, according to the author's previous study[8], the optimum concentration for obtaining a local maximum heat transfer coefficient of the PCM slurry flow was at 20 mass percent in the case of uniform microcapsule particles of 1.5 μm in small size diameter. Therefore, the present experimental study was performed to examine the heat transfer enhancement of large size microcapsules (17 μm in diameter) PCM slurry flow against the uniform PCM slurry with small size microcapsules (1.5 μm in diameter) PCM slurry flow.

The plural microcapsule PCM slurry with different diameters can be applied to heating air condition system in winter and cooling one in summer by encapsulated different melting point PCMs into each capsules.

The present experiments are carried out to investigate melting heat transfer characteristics of plural PCM slurries flow with different microcapsule diameters and different melting points in a straight heat transfer pipe. Moreover, the present study has been made to elucidate the relatio- nship between transmitted heat of plural PCM slurries flow and pumping power.

2. Physical Characteristics and Properties of PCM Slurry

According to the previous results of author's study[8], it was reported that the optimum concentration to reach a local maximum heat transfer of PCM slurry flow in a pipe was $C_{sma} = 0.2$ in the case of uniform small size microcapsule particles of 1.5 μm in an average diameter.

In which its physical properties were as follows:

- Phase change material: n-tetradecane
- Melting temperature of the PCM particle : 278.9 [K]
- Latent heat of melting: L=229[kJ/kg]

To make plural PCM slurry with different sizes of microcapsule particles, large size microcapsule particles of 17 μm in an large diameter were added and mixed well into the uniform PCM slurry at a concentration, C_{sma} = 0.2 with small size of PCM particle around a 1.5 μm average diameter. The PCM particle with large size was the paraffin wax at a melting point of 318.2K, while the PCM particle with small size was the paraffin wax at a melting point of 278.9K. In the present study, the PCM particle with large size did not work as a phase change material since experiments were performed below 318.2K.

In Fig. 1, the concentration of large size particle, C_{big}, as parameter corresponds to the mass ratio of the PCM particles with a large diameter of 17 μm to those with a small diameter of 1.5 μm. The external appearance of PCM (total concentration, C_{tot} = 0.25 in defined in Eq. (2)) slurry is shown in Fig. 2. From this figure, it is seen that plural PCM slurry has a white color and good fluidity so this slurry can be transported in a pipe.

The average diameter, d_{ave}, of the plural PCM microcapsule particles dispersed in water is calculated by an arithmetic average method of mass and diameter as Eq. (1) used these two different diameters of PCM particles and also the total concentration, C_{tot}, is also calculated by Eq. (2).

$$d_{ave} = d_{sma}(1 - C_{big}) + d_{big}C_{big} \tag{1}$$

$$C_{tot} = \frac{C_{sma} + C_{sma}C_{big}}{1 + C_{sma}C_{big}} \tag{2}$$

Where, C_{big} is the mass concentration of PCM particle with large size according to small size PCM slurry which has no phase change in this experimental temperature range.

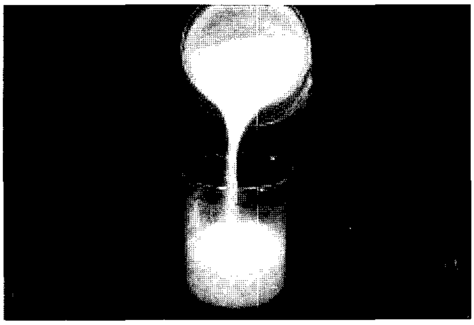


Fig. 2 Appearance of plural PCM slurry

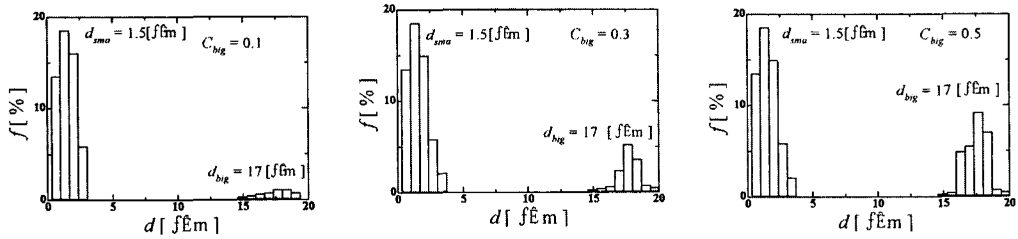


Fig. 1 PCM particle distribution

The thermophysical properties such as density, ρ_b, and specific heat, Cp_b, of the different diameters PCM slurry are estimated using the additional properties law[7] presented in Eqs. (3), (4).

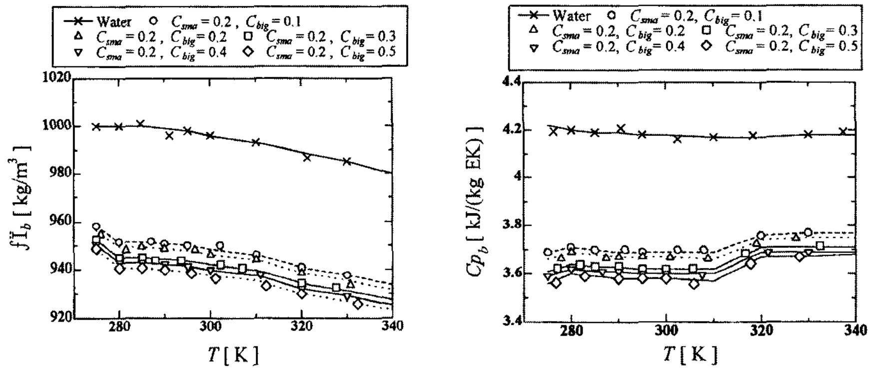
Fig. 3 shows the measured data of density, specific heat, thermal conductivity and viscosity with temperature. The measured data of them in the present study by the previous method are in a good agreement with Eqs. (3) and (4) within ±3 percent and ±5 percent, respectively.

It is understood that the additional properties law can be applied to estimate the thermophysical properties of this plural PCM slurry in both liquid phase and solid phase of phase change material dispersed in water.

The thermal conductivity, k_b, and viscosity, μ_b, of the slurry are estimated by using the correlations of Maxwell[9] and Vand[10], as seen by solid lines in Fig. 3.

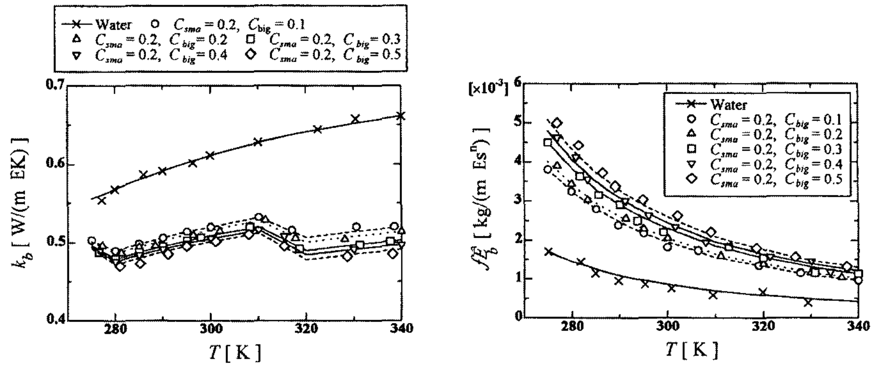
They were compared with the measured data (symbols in Fig. 3) in Fig. 3 by the previous measuring method[7] and they coincided with them within ±7 percent and ±5 percent, respectively.

Where, the solid lines in Fig. 3 indicate the calculated results of Eqs. (5) and (6).



Density

Specific heat



Thermal conductivity

Viscosity

Fig. 3 Thermophysical properties of the plural PCM slurry (symbols : experimental data, lines : estimated by Eqs. (3)~(6))

Density, $\rho_b : \rho_b = \rho_w \times (1 - C_{tot}) + \rho_p \times C_{tot}$ (3)

Specific heat,

$Cp_b : Cp_b = Cp_b C_{tot} + Cp_w \times (1 - C_{tot})$ (4)

Thermal conductivity,

$$k_b : \frac{k_b}{k_w} = \frac{2 + \frac{k_p}{k_w} + 2C_{tot}(\frac{k_p}{k_w} - 1)}{2 + \frac{k_p}{k_w} - C_{tot}(\frac{k_p}{k_w} - 1)} \quad (5)$$

Viscosity, $\mu_b : \frac{\mu_b}{\mu_w} = (1 - C_{tot} - 1.16C_{tot}^{2})^{-2.5}$ (6)

3. Experimental apparatus and Method

Fig. 4 indicates the schematic diagram of experimental apparatus used to examine the characteristics of flow and heat transfer phenomenon of the plural PCM slurry. The experimental apparatus consisted mainly of a heat transfer horizontal tube as a test section maintained at constant wall heat flux, the PCM slurry circulating part and a cooling tank with refrigerator to make PCM particles solid phase dispersed in water. And also the detail of the test section is shown in Fig. 4. The test section was made up of a stainless steel tube of 15mm in inside diameter, 0.8mm in thickness and 5.85m in length.

The constant heating wall heat flux condition was obtained by supplying directly DC electricity on the stainless steel tube from a DC power supply. The uncertainty of obtained data on the heat flux, q, was estimated within ±2 percent by measuring the electric current with a precision amperometer and voltage with a precision voltmeter across the stainless steel tube.

In order to prevent the heat loss from the test section to the circumference environment, two layer thermal insulators composed of 20mm thickness glass wool insulating material and 30mm thickness urethane foam insulating material were installed around the test section. As a result, the total heat loss was controlled within ±3 percent as compared with the total heat transmitted to the plural PCM slurry. The measuring accuracy of heat transfer coefficient, h, for only water flow by a preliminary experiment was also coincided with the reference value[11] within ±5 percent and the uncertainty of obtained temperature data with T-type thermocouple 0.1mm in diameter was estimated as ±2 percent by using a standard thermometer.

In order to measure the pressure loss difference, ΔP, of PCM slurry flow between inlet and outlet of the test section, a precision manometer (measuring error within ±1 percent) was set between 3mm diameter pressure drop taps mounted on the inlet and outlet of the test tube. The friction factor, f_b, of the plural PCM slurry was calculated by following Eq. (7).

The mass flow rate of test fluid was estimated by the weighting method of a precision scale (measuring error within ±1 percent). The uncertainty of mass flow rate data was estimated about ±1 percent as regards to the reading error of the scale.

$$f_b = \frac{\Delta P_b / l_{te}}{(1/2)\rho_w U_b^2 / D}, \quad f_w = \frac{\Delta P_w / l_{te}}{(1/2)\rho_w U_b^2 / D} \quad (7)$$

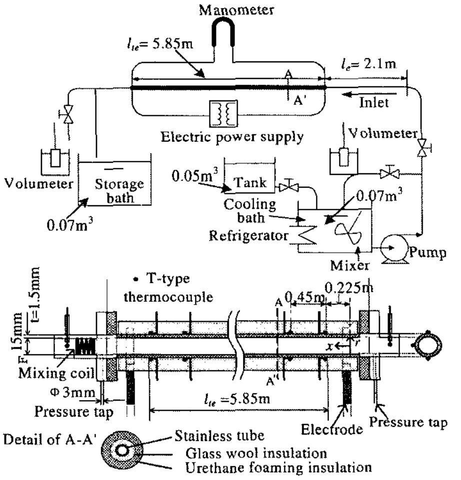


Fig. 4 Schematic diagram of experimental apparatus

Table 1 Experimental conditions

Concentration of small particle (Main concentration of slurry)	C_{sma} = 0.2
Concentration of big particle	C_{big} = 0.1~0.5
Heat flux [kW/m^2]	q_{hw} = 1.3, 1.6
Modified Reynolds number	Re' = 500~6000

4. Experiment Results and Discussion

Friction Factor. Fig. 5 shows the relationship between friction factor, f, and Reynolds number, Re, for water flow in the test section. From Fig. 5, it is clear that the data of friction factor for water, fw, in the laminar and turbulent region show a good agreement with the correlations of Hagen-Poiseuille and Blasius within ±3 percent. On the other hand, the data of friction factor, f_b, for the plural PCM slurry flow with various concentrations of the PCM particles, C_{big}, show the different tendency from the data for water flow in the turbulent region in Fig. 6. The friction factor value of different diameters PCM slurry, f_b, exists between the correlations of Blasius for Newtonian fluid (f_b=16/Re') and non-Newtonian fluid (f_b=0.332$Re'^{-0.55}$) by Ng[12].

These data revealed that the generation of turbulence for the plural PCM slurry flow was suppressed by the Toms' effect of microcapsule particles dispersed in water in the turbulent region as a drag reduction surfactant additives in a water flow. Also the friction factor of the plural PCM slurry, f_b, increases with an increase in concentration, C_{big}, of PCM particles. The obtained results for f_b show the same tendency as the experimental ones of Choi[6].

Heat transfer coefficient. Fig. 7(a) presents the variation of local Nusselt number, Nu_x, with nondimensional axial distance, χ, for the plural PCM slurries at various modified Reynolds number, Re'.

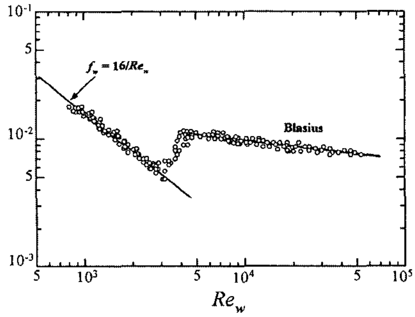


Fig. 5 Friction factor of water

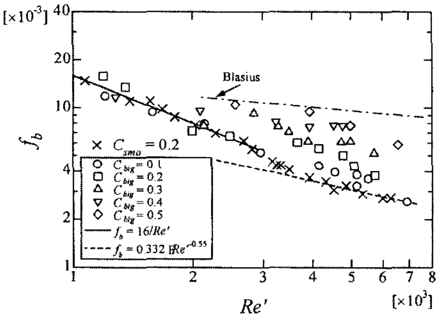


Fig. 6 Friction factor of different diameters PCM slurry

The nondimensional numbers used in the present study were defined as follows;

$$\left.\begin{array}{l}
\text{Local Nusselt number : } Nu_x=\dfrac{h_{hx}D}{K_b} \\[2ex]
\text{Nondimensional axial distance: } \chi=\dfrac{x}{D}\cdot\dfrac{1}{\mathrm{Re'}\cdot\mathrm{Pr'}} \\[2ex]
\text{Modified Reynolds number based on} \\
\text{power viscosity law :} \\
\quad \mathrm{Re'}=8^{1-n}\left[\dfrac{3n+1}{4n}\right]^{-n}\left[\dfrac{\rho_b U^{2-n}D^n}{\mu_b}\right] \\[2ex]
\text{Modified Prandtl number based on} \\
\text{power viscosity law: } \mathrm{Pr'}=\left[\dfrac{3n+1}{4n}\right]^{-n}\left[\dfrac{8U}{D}\right]^{n-1}\dfrac{\mu_b Cp_b}{k_b} \\[2ex]
\text{Stefan number: } Ste_b=\dfrac{Cp_b\rho_b\,|\,q_{hw}R/k_b|}{C_{tot}L\rho_p}
\end{array}\right\} \quad (8)$$

The open symbols in Fig. 7(a) shows the local Nusselt number of single PCM slurry having small size diameter of PCM particle of 1.5 μm in an average diameter. The solid and dash line in the Fig. 7(a) are the correlation equations of the only slurry by Bird[13], [14] which were derived by data without phase change. It is seen that the data of local Nusselt number for single PCM slurry are greater than those calculated from the correlation equations without phase change. These increase in Nu_x for the single PCM slurry having small size particles results from keeping the thermal boundary temperature at around a melting point of the PCM particles due to latent heat generation during phase change.

Furthermore, it is clear from Fig. 7(a) that the closed symbol's data of Nu_x for the plural PCM with two kinds of PCM particles in different diameters are over those for single PCM slurry as indicated in open symbols. This is due to the result that the PCM particles in small size (1.5 μm in diameter) generate latent heat by melting, while those in large size (17 μm in diameter) don't generate latent heat due to operating below its melting point of 318.2K. This increase in Nu_x for the plural PCM slurry would be brought about by the microconvection around the plural particles due to the mixed convection of natural (buoyant force by PCM particles) and forced convections.

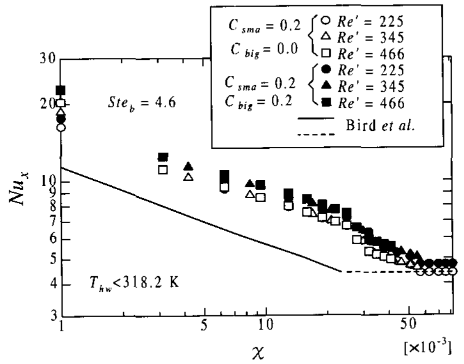


Fig. 7(a) Variation of local Nusselt number

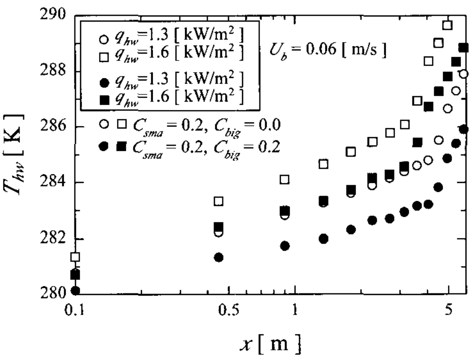


Fig. 7(b) Surface wall temperature distribution of test section tube

The wall surface temperature data of heating tube wall surface, T_{hw}, for the plural PCM slurry as shown in Fig. 7(b) by the closed symbols, are lower than those for single PCM slurry in small size of the PCM particles. These results of wall surface heat transfer coefficient under the constant heat flux condition, h_{hx}, correspond to the results of local Nusselt number, Nu_x, in Fig. 7(a) as indicated in Eq. (9).

$$h_{hx}=\frac{q_{hw}}{(T_{hw}-T_b)} \tag{9}$$

Fig. 8 shows the variation of the mean Nusselt number, Nu_m, with modified Reynolds number, Re'. It is noticed that the data of Nu_m for the plural PCM slurry are greater than those for single PCM slurry (symbol: ◇) in small size of PCM particles and the slurry without phase change (symbol: ×). As the concentration ratio of large size PCM particles in the plural PCM particles, C_{big}, increases, the mean Nusselt number, Nu_m, is increased by mixing effect (microconvection) by large size PCM particles. As a result, It is seen that value of Nu_m for $C_{big}=0.5$ is 2.8 times greater than that for small size PCM particles without phase change.

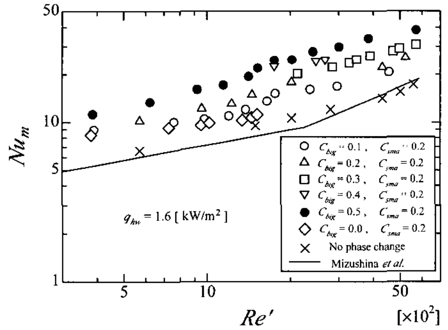


Fig. 8 Mean Nusselt number

Velocity Profile of the PCM Slurry in the Radial Direction. Fig. 9 presents the nondimensional velocity (U_r /U_{max}) profile in the nondimensional radial direction (r/R) for a mixture of water and fine plastic beads (density ρ= 995kg/m^3, 20 μm in diameter) at a concentration of 1000ppm. It is seen that nondimensional velocity profile, U_r /U_{max}, of water-plastic beads slurry is well agreed with Hagen-Poiseuille's equation so it is reasonable to use Ultra Sonic Velocimeter (UVP) in order to measure the velocity profile of the plural PCM slurry and single PCM slurry in small size of PCM particles.

From Fig.10, it is seen that the closed triangle symbol's data of nondimensional velocity profile (U_r /U_{max}) for single PCM slurry in small size of PCM particles are above those of water as Newtonian fluid at near the wall surface ($0.7 \leq r/R \leq 1.0$). Moreover, in the case of the plural PCM slurry for C_{big}=0.5 and C_{sma}=0.2 (solid symbol in Fig. 10), the value of nondime- nsional velocity (U_r/U_{max}) becomes greater than those of single PCM slurry in a small size. This difference of U_r/U_{max} between the plural PCM slurry and single PCM slurry would be explained by the fact that the mixing effect by large size PCM particles appear in the PCM slurry flow.

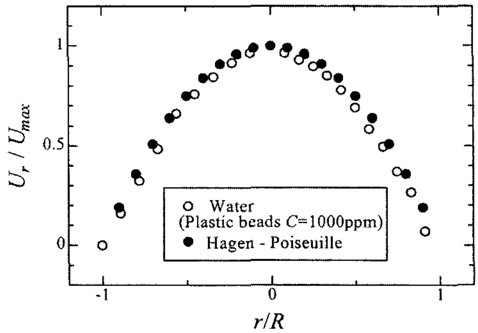


Fig. 9 Nondimensional velocity profile of water in the radial direction

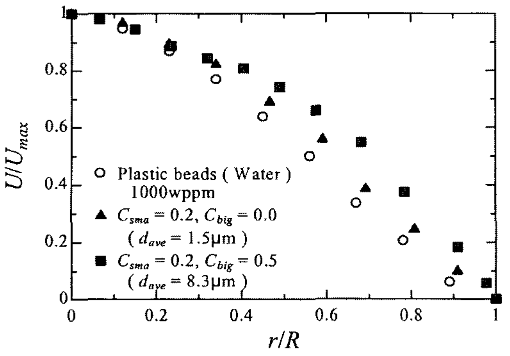


Fig. 10 Nondimensional velocity profiles in the radial direction

This variation in nondimensional velocity profile for the plural PCM slurry could be explained by using the momentum model of spherical particle of PCM as shown in Fig. 11. First, the momentum balance on spherical particle (PCM particle) consists of drag, B, and lift, Z, forces in the axial direction and radial direction and they can be expressed by Eq. (10) using these forces in Newton's law of momentum.

$$\sum F_x = \rho_p V_p\left(\frac{dU_x}{dt}\right),\quad \sum F_r = \rho_p V_p\left(\frac{dU_r}{dt}\right) \tag{10}$$

Moreover, the balance equation in the axial direction derived like Eq. (11).

$$-Z_x - B_x = \rho_p V_p\left(\frac{dU_x}{dt}\right),\quad -\rho_p V_p g + Z_r - B_r = \rho_p V_p\left(\frac{dU_r}{dt}\right) \tag{11}$$

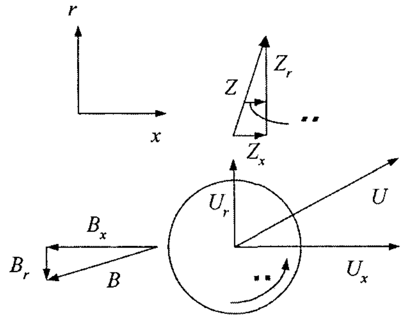


Fig. 11 Momentum model of sphere

Where, the drag and lift forces are defined as,

$$Z = \frac{1}{2}\rho_p C_Z U^2 S,\quad B = \frac{1}{2}\rho_p C_B U^2 S \tag{12}$$

Where, C_Z and C_B are coefficients of lift force and drag force, respectively. The values of these coefficients are shown in Fig. 12, where S is the projected area of particle.

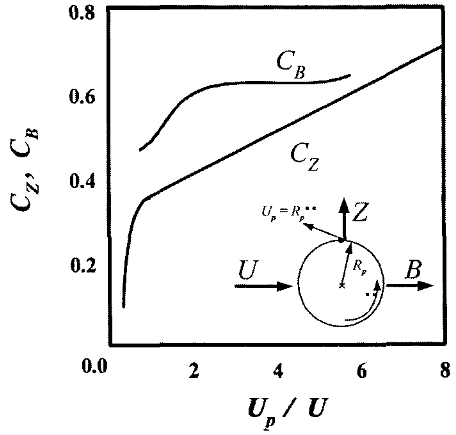


Fig. 12 Coefficient of lift force and drag force of sphere

The approximation of the motion for microcapsule particle can be deduced from the above equations as follows.

$$\left.\begin{aligned} -\frac{1}{2}\rho_p C_B U_x^2 S &= \rho_p V_p\left(\frac{dU_x}{dt}\right) \\ -\rho_p V_p g + \frac{1}{2}\rho_p C_Z U_x^2 S &= \rho_p V_p\left(\frac{dU_r}{dt}\right) \end{aligned}\right\} \tag{13}$$

After developing the above equations in the radial direction, the velocity profile of PCM slurry at the instantaneous time, U_r, can be defined by equation (14) and velocity of slurry flow in a pipe can be arranged as indicated in Eq. (15).

$$U_r = -gt - \frac{C_Z}{C_B}\left(\frac{U_{x0}}{1+\frac{\rho_p C_B S U_{x0} t}{2\rho_p V_p}}\right) = -gt + \frac{C_Z}{C_D}(U_{x0} - U_x) \tag{14}$$

$$U^2 = U_x^2 + U_r^2 = U_x^2\left[1+\left(\frac{U_r}{U_x}\right)^2\right] \tag{15}$$

Fig. 13 shows the nondimensional velocity profiles (U_r/U_{max}) of water (solid line), single PCM slurry (symbol:×) and plural PCM slurries for various C_{big}. It is seen from Fig. 13 that values of U_r/U_{max} increase with an increase in concentration ratio of large size PCM particles, C_{big}, as shown in Fig. 10. Therefore, it is concluded that the mixing effect of large size PCM particles exert an influence on heat transfer enhancement in plural PCM slurry.

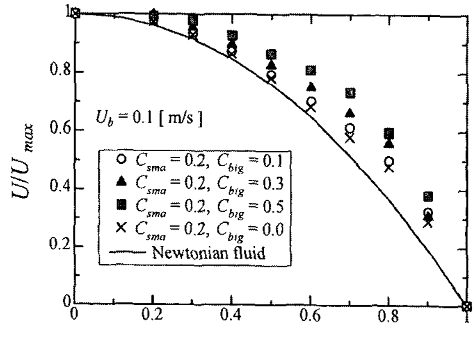


Fig. 13 Calculated nondimensional radial direction velocity profile

Heat Transfer and Pumping Power of the PCM slurry. Here, referring to application of the plural PCM slurry, it is necessary to investigate the relationship between the transmitted heat in a heat exchanger, Q_{tr}, and its pumping power, W_{th}.

First, the transmitted heat quantity through a circular tube for the plural PCM slurry, Q_{tr}, was calculated from the following Eq. (16) as the sum of latent heat quantity and sensible heat quantity exchanged through a heat exchange tube.

$$Q_{tr} = m_b \times (Cp_b \times \Delta T + L_b) \tag{16}$$

In Eq. (16), ΔT corresponds to temperature difference of the plural PCM slurry at the inlet and outlet position of a circular tube according to experimental parameter conditions.

The theoretical pumping power, W_{th}, is calculated by measuring pressure drop difference, ΔP, of the plural PCM slurry at the inlet and outlet position of the circular tube as mentioned in the former section as follows.

$$W_{th} = \frac{D^2}{4}\pi U_b \Delta P_b \tag{17}$$

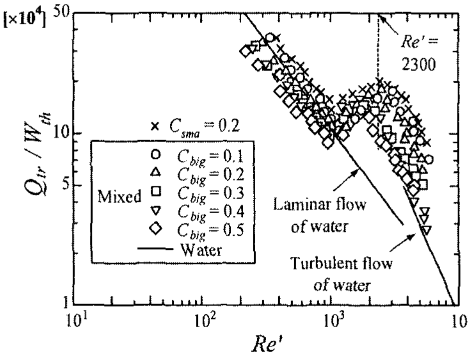


Fig. 14 Relationship between Re' and Q_{tr}/W_{th}

Fig. 14 shows the variation of the ratio of Q_{tr} to W_{th} for the plural PCM slurry with modified Reynolds number, *Re′*. It is clear that the value of Q_{tr}/W_{th} decreases with increasing the concentration, C_{big}, of the PCM particles in large size. This tendency is caused by the fact that the increase in pumping power based on the viscosity of the plural PCM slurry surpasses the increase in the transmitted heat quantity as the concentration, C_{big}, increases. It is intriguing that there appears a local maximum of Q_{tr}/W_{th} at around $Re'=2300$.

5. Characteristic of Heat Transfer and Drag Reduction.

Fig. 15 shows the relationship between the friction factor ratio, *DR*, based on drag reduction effect and nondimensional heat transfer parameter ratio, *HTR*, of Newtonian fluid and the plural PCM slurry, respectively. The definitions of friction factor ratio and nondimensional heat transfer parameter ratio are as follows.

$$DR = \frac{f_{nf} - f_b}{f_{nf}}, \quad HTR = \frac{j_{Hnf} - j_{Hb}}{j_{Hnf}},$$
$$j_{Hnb} = St \cdot \mathrm{Pr}'^{2/3}, \quad j_{Hnf} = St \cdot \mathrm{Pr}^{2/3} \qquad (18)$$

Where, f_{nf} and j_{Hnf} correspond to the friction factor and nondimensional heat transfer parameter of water as Newtonian fluid, respectively, and also f_b and j_{Hnd} correspond to those for the plural PCM slurry.

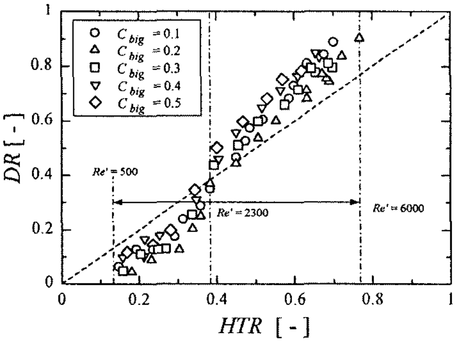


Fig. 15 Relationship between HTR and DR

The data in Fig. 15 indicate that the tendency of experimental data varies on the boundary at around $Re'=2300$. In the range of $500<Re'<2300$, the value of j_{Hb} is greater than that of j_{Hnf} due to the phase change effect of the PCM particles in a small size, so those data are below of the dashed line. In contrast, in the range of $2300<Re'<6000$, the data for the PCM slurry are higher than the dashed line due the effect of drag reduction by PCM microcapsules as mentioned above. Concerning the application of the plural PCM slurry to the heat carrier medium for a heat exchanger, these results reveal that the modified Reynolds number should be controlled in the turbulent region ($Re'>2300$) to need the effect of drag reduction. On the contrast, in order to need the effect of heat transfer enhancement, the modified Reynolds number must be controlled in the laminar region ($Re'<2300$).

6. Concluding Remarks

The heat transfer enhancement of the plural PCM slurry has mainly been investigated experimentally under the flow conditions of laminar and turbulent flow in a circular tube with a constant wall heat flux. The influence of latent heat evolved during the phase change process and microconvection around the PCM particles were clarified for the single and plural PCM microcapsule slurries. The main conclusions and the results of investigation are summarized as follows :

- The generation of turbulence in the

plural PCM slurry with different diameters of PCM particles flow was suppressed by the Tom's effect of PCM particles dispersed in water in the turbulent region like drag reduction surfactant additives.

- The velocity profile of the PCM slurry in the radial direction was calculated by the Newton's law of momentum. And that was clarified the existence of microconvection around the PCM particle
- The local Nusselt number of the plural PCM slurry showed greater value than that without phase change due to the microconvection effect and latent heat generation during melting process of phase change material dispersed in water.
- Using the concept of theoretical pumping power, the relationship between Q_{tr}/W_{th} and Re' was clarified that the apparent difference existed at $Re'=2300$.
- Concerning the application of the plural PCM slurry to heat transfer medium of heat exchanger, it was concluded that the modified Reynolds number should be controlled in the turbulent region ($Re' > 2300$) to need the effect of drag reduction. On the contrast, the modified Reynolds number should be controlled in the laminar region ($Re' < 2300$) in order to need the effect of heat transfer enhancement.

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