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Heat Transfer Characteristics of Liquid-Solid Suspension Flow in a Horizontal Pipe

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Particles in liquid-solid suspension flow might enhance or suppress the rate of heat transfer and turbulence depending on their size and concentration. The heat transfer characteristics of liquid-solid suspension in turbulent flow are not well understood due to the complexibility of interaction between solid particles and turbulence of the carrier fluid. In this study, the heat transfer coefficients of liquid-solid mixtures are investigated using a double pipe heat exchanger with suspension flows in the inner pipe. Experiments are carried out using spherical fly ash particles with mass median diameter ranging from 4 to 78μm. The volume concentration of solids in the slurry ranged from 0 to 50% and Reynolds number ranged from 4,000 to 11,000. The heat transfer coefficient of liquid-solid suspension to water flow is found to increase with decreasing particle diameter. The heat transfer coefficient increases with particle volume concentration exhibiting the highest heat transfer enhancement at the 3% solid volume concentration and then gradually decreases. A correlation for heat transfer to liquid-solid flows in a horizontal pipe is presented.

Key Words : Liquid-Solid Flow, Two Phase Flow, Convection Heat Transfer, Double Pipe Heat Exchanger, Particle-Turbulence Interaction

Nomenclature

A : Area,
C_p : Specific heat, J/kg · ℃
C_{po} : Specific heat of hot oil, J/kg · ℃
C_S : Solid volume concentration, % or fraction
d_p : Particle diameter, μm
D : Pipe diameter, m
D_h : Hydraulic diameter of outer pipe, m
h : Convection heat transfer coefficient, W/m^2 · ℃
h_o : Convection heat transfer coefficient of hot oil,W/m^2 · ℃
k : Thermal conductivity, W/m · ℃
k_o : Thermal conductivity of hot oil, W/m · ℃
k_w : Thermal conductivity of pipe, W/m · ℃
L : Pipe length, m
$\dot{m}$: Mass flow rate, kg/sec
$\dot{m}_o$: Mass flow rate of hot oil, kg/sec
q : Heat transfer rate, W
T : Temperature, ℃
u : Velocity, m/sec
U : Overall heat transfer coefficient, W/m^2 · ℃
ρ : Density, kg/m^3
μ : Viscosity, N · sec/m^2
$\Delta P/\Delta L$: Pressure drop per unit pipe length, Pa/m
ΔT_{lm} : Log mean temperature difference, ℃

Subscripts

f : Fluid
i : Inner side
o : Outer side
p : Particle
s : Slurry (liquid-solid mixture)
w : Wall side

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Dimensionless Parameters

Nu : Nusselt number $\frac{hD}{k}$

Pr : Prandtl number $\frac{\mu C_p}{k}$

Re : Reynolds number $\frac{\rho u D}{\mu}$

1. Introduction

Heat transfer from a solid surface to a liquid-solid suspension in vertical or horizontal transport is important in the design of heat exchangers, driers, fluidized beds and slurry pipeline reactors. Concentrated suspension flow has been applied to many chemical process in the form of a slurry reactor combined with simultaneous transportation of solid material. Any attempt to design a slurry reactor necessarily requires a knowledge of its characteristics such as the behavior of the suspension pressure drop and the rate of heat transfer related to the supply or removal of the heat of reaction (Lee and Borner, 1987).

The hydrodynamic and heat transfer characteristics of suspensions in turbulent flow are not well understood owing to the complexibility of interactions between solid particles and turbulence of the carrier fluid (Kim, Byong Joo, 1998). Particles can enhance or suppress turbulence, depending on their size and concentration, or they may increase the rate of heat transfer (Zisselmar and Molerus, 1979).

Richardson et al. (1976) and Haid et al. (1994) showed that the values of the heat transfer coefficient in liquid-solid fluidized beds could be up to 8 times higher than for single phase forced convection owing to the increased turbulence caused by the fluidized particles (Moon, 1998). Hetsroni and Rozenblit (1994) investigated on the heat transfer to a liquid-solid mixture in a flume. The heat transfer of liquid-solid suspension in pipes was investigated in several experimental studies (Harada et al., 1985; Ozbelge and Somer, 1994). There are only limited studies on heat transfer in liquid-solid flows using particles smaller than $12\mu m$ and particle volume concentration over 10%. Further experimental work is necessary in this field to confirm the existing correlations and theoretical results, and to obtain the new correlations covering wider range of relevant parameters.

The purpose of this study is to investigate the effect of particles on the heat transfer of liquid-solid suspension flow in a horizontal pipe using the spherical coal fly ash particles suspended in water. Experiments are carried out using the spherical fly ash particles with mass median diameter ranging from 4 to $78\mu m$. The volume concentration of solids in the slurry ranged from 0 to 50% and Reynolds number ranged from 4, 000 to 11,000. A correlation for heat transfer to liquid-solid flows is presented.

2. Heat Transfer Analysis

Particles in liquid-solid suspension flow might enhance or suppress the rate of heat transfer and turbulence depending on their size and concentration. To investigate the heat transfer characteristics of liquid-solid suspension in turbulent flows, the convection heat transfer coefficient was obtained as a function of particle size and concentration. In this study, the double pipe heat exchanger shown in Fig. 1 is used with liquid-solid suspension flowing in the inner pipe and hot oil fluid flowing in the outer pipe with counter flow arrangement.

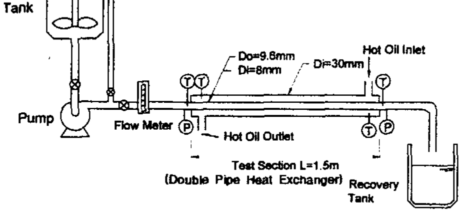

Fig. 1 Schematic diagram of experimental apparatus for measuring the heat transfer rate of liquid-solid suspension flows in the horizontal pipe

The convection heat transfer coefficient of liquid-solid suspension flow (h_s) can be obtained from the inlet and outlet temperature, mass flow rate, surface area, and heat transfer rate of the double pipe heat exchanger. The heat transfer rate (q) from the outer pipe wall heated by hot oil to the inner pipe of suspension flow is described as follows.

$$q = UA\Delta T_{lm} \tag{1}$$

Here U denotes the overall heat transfer coefficient and ΔT_{lm} denotes the log mean temperature difference as follows.

$$\frac{1}{UA} = \frac{1}{h_s A_i} + \frac{\ln D_0/D_i}{2\pi k_w L} + \frac{1}{h_0 A_0} \tag{2}$$

$$\Delta T_{lm} = \frac{(T_{oi} - T_{so}) - (T_{oo} - T_{si})}{\ln\left[\frac{(T_{oi} - T_{so})}{(T_{oo} - T_{si})}\right]} \tag{3}$$

To get the convection heat transfer coefficient of liquid-solid suspension (h_s), the heat transfer rate (q) and the heat transfer coefficient of hot oil flowing in the outer pipe (h_o) should be obtained experimentally and theoretically by heat balance in the hot oil flow. The heat transfer rate (q) can also be obtained through the measurements of inlet and outlet temperatures in liquid-solid suspension flow.

$$\begin{aligned} q &= (\dot{m}_f C_{pf} + \dot{m}_p C_{pp})(T_o - T_i) \\ &= \dot{m}_o C_{po}(T_{oi} - T_{oo}) \end{aligned} \tag{4}$$

The heat transfer coefficient of hot oil flowing in the outer pipe (h_o) can be expressed using the Dittus-Boelter equation as follows (Incropera and De Witt, 1996).

$$Nu = \frac{h_o D_h}{k_o} = 0.023 Re^{4/5} \mathrm{Pr}^{0.3} \tag{5}$$

Here k_o is the thermal conductivities of hot oil flowing in the outer pipe.

In summary, the convection heat transfer coefficient (h_s) can be obtained from the measurements of heat transfer rate (q), and inlet/outlet temperatures of the inner suspension flow and outer temperatures of the inner suspension flow and outer fluid as a function of particle size, solid concentration, and Reynolds number.

3. Experimental Apparatus and Procedure

Figure 1 shows a schematic diagram of the experimental apparatus for investigating the heat transfer characteristics of liquid-solid suspension flow in a horizontal pipe. The system consists of a feed tank with an agitator, a feeding pump (PHIL TEC, PT-50), a double pipe heat exchanger, and a recovery tank. The slurry of liquid-solid suspension is prepared in a feed tank with the agitator for uniform particle distribution. The feeding pump circulates the slurry from the tank to the test section of a double pipe heat exchanger. Thorough mixing is further ensured by means of a by-pass line recycling the slurry into the tank. The test section consists of a 8mm diameter stainless steel pipe inside a 30mm diameter stainless steel pipe of 1.5m length. Thermocouples (K-type) and pressure gages are attached to the inlet and the outlet of test section to measure the both side temperatures and pressure drop. For heat transfer studies, liquid-solid suspensions flowing in the inner horizontal pipe are heated with hot oil (Shell, Thermia Oil Type B) flowing the outer pipe with the counter flow.

Table 1 shows the physical properties of the spherical coal fly ash particles and water as the test particles and fluid (Popiel and Wojtkowiak, 1998). The spherical fly ash is the density of 2,270kg/m^3, specific heat of 745J/kg · ℃ and thermal conductivity of 1.38 W/m · ℃. Particle suspensions used in this study are the coal fly ash

Table 1 Physical Properties of Test Particles and Liquids

Items	Test Particle	Test Liquid
Material	Coal Fly Ash	Water(at 25℃)
Components	SiO_2(51%), Al_2O_3(30%), Fe_2O_3(4%), etc	-
Mass median diameter(μm)	4, 8, 13, 34, 78	-
Density (kg/m^3)	2,270	997
Specific heat (J/kg · ℃)	745	4,179
Thermal conductivity (W/m · ℃)	1.38	0.613
Viscosity (N · sec/m^2)	-	855×10^{-6}

Table 2 Test Conditions for the Heat Transfer Tests in Liquid-Solid Mixture

Parameter	Range
Particle size(d_p), μm in mass median diameter	4, 8, 13, 34, 78
Particle volume concentration(C_s), %	0~50
Reynolds number(Re)	4,000~11,000
Prandtl number(Pr)	3.8~5.0
Flow velocity(u), m/s	0.33~1
Water inlet temperature(℃)	24.5
Hot oil inlet temperature(℃)	100

particles of 4, 8, 13, 34, and 78μm sizes in mass median diameter obtained from the wet sieving method.

Table 2 shows the test conditions for heat transfer tests in liquid-solid mixture. The test conditions are summarized as the particle size of 4~78μm in mass median diameter, the particle volume concentration of 0~50% in the solid-liquid suspension flow, the Reynolds number of 4,000~11,000, the Prandtl number of 3.8~5.0, and the flow velocity of 0.33~1.0m/s. The difference of hot oil temperature in the inlet and outlet is 5℃. The Renolds number and the Prandtl number are described as follows.

$$Re=\frac{\rho uD}{\mu} \tag{6}$$

$$\mathrm{Pr}=\frac{\mu C_p}{k} \tag{7}$$

4. Results and discussion

4.1 Heat transfer rate for liquid-solid suspension

Figure 2 shows the measured heat transfer coefficient of liquid-solid suspension flow as a function of particle volume concentration and Reynolds number for the particle size of 13μm in mass median diameter. For the Reynolds number of 7,000, the heat transfer coefficients for the particle volume concentration at 0, 3, 30, and 50% are found to be 3,850, 4,600, 3,000, and 2,400 W/m^2 · ℃, respectively. The heat transfer coefficient increases with particle volume concentration up to 3%, and then gradually decreases. It may be attributed to modifications of pipe flow turbulence due to liquid-solid interaction. It is believed that the particles do not follow the fluid motion due to their high inertia and cross from one eddy to another in the process transferring momentum and cause mixing. Heat is transferred into the fluid by transient heat conduction from the heat transfer surface to the adjacent liquid layer. In the wake of particles departing from the heat transfer surface, the hot liquid layer is transported into the liquid bulk and replaced by cooler liquid. Some heat is also transferred by conduction to the particles while they are in contact with the heat transfer surface. The reverse applies to high solid concentrations. In this range the turbulence is hampered by the growing particle-particle interaction, which explains the marked decrease of heat transfer in the range of high solids concentrations. It is believed that turbulence suppression may be due to an increase in apparent viscosity owing to the particles.

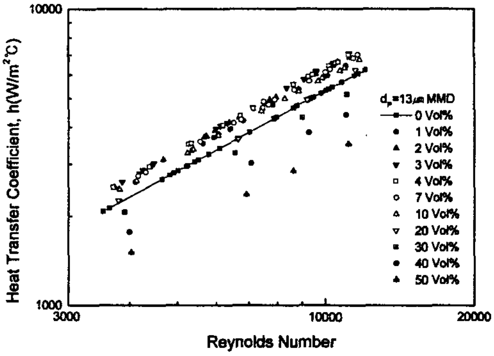

Fig. 2 Experimental results of the heat transfer coefficient as a function of solid concentration and Reynolds number at the particle diameter of 13μm

Figure 3 shows the comparison of the heat transfer coefficient ratio (h_s/h_f) for a liquid-solid suspension flow (h_s) divided by that for clear water (h_f) as a function of volume concentration for the particle size of 13μm in mass median diameter. For the Reynolds number of 7,

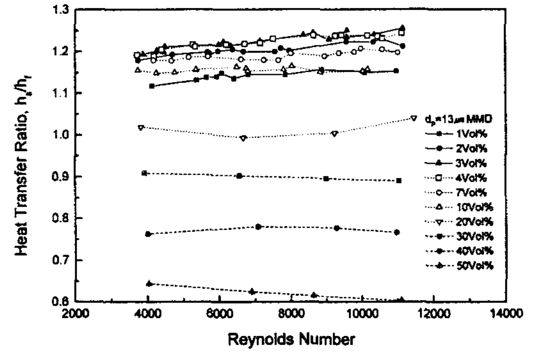

Fig. 3 Comparison of the heat transfer ratio as a function of solid concentration and Reynolds number at the particle size of 13μm

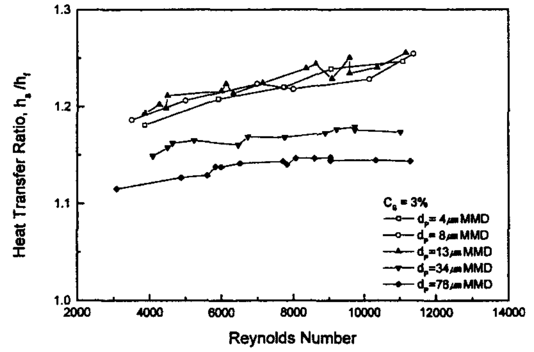

Fig. 4 Experimental results of the heat transfer ratio as a function of particle size and Reynolds number at the solid volume concentration of 3%

000, the heat transfer coefficient ratio for the particle volume concentration at 1, 3, 30, and 50% is found to be 1.15, 1.22, 0.91, and 0.62, respectively. The heat transfer coefficient ratio increases about 20% at 3% particle concentration and decreases about 38% at 50%. The heat transfer coefficient ratio increases with particle volume concentration but it begins to decrease when the volume concentration exceeds about 3% due to modifications of pipe flow turbulence due to liquid-solid interaction.

Figure 4 shows the test results of the heat transfer coefficient ratio as a function of particle size ranging from 4 to 78μm at the particle volume concentration of 3%. For the Reynolds number of 7,000, the heat transfer coefficient ratios for the particle size of 4, 34, and 78μm in mass median diameter is found to be 1, 22, 1.17, and 1.14, respectively. The heat transfer coefficient ratio shows a tendency to increase with decreasing particle diameter but it never increase when particle diameter is below 13μm. It is found that the smaller particles cause more increase in heat transfer efficient, whereas the heat transfer enhancement is insignificant for particles smaller than 13μm.

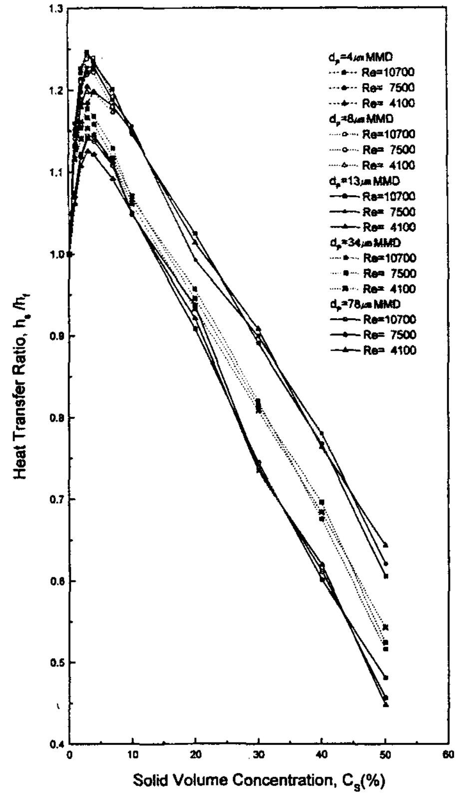

Fig. 5 Summary of test results for heat transfer ratio as a function of particle size and solid concentration

Figure 5 shows the summary of experimental results for the heat transfer ratio as a function of particle size, Reynolds number and solid concentration. For all the particle size and Reynolds number, heat transfer is found to increase with particle volume concentration up to 3% due to the increase of turbulence intensity and then gradually decrease with increased particle concentration due to turbulence suppression by the increase in apparent viscosity due to the particles. For particle volume concentration around 3%, the presence of the coal fly ash particles of 13akal diameter leads to an increase in the heat transfer rate up to 25%.

4.2 Heat transfer correlation

The dimensional analysis is used in the derivation of a heat transfer correlation of liquid-solid suspension flow. The dimensionless variables used to account for the effect of particles on the heat transfer rate are Nusselt number (Nu_s), Reynolds number (Re_s), Prandtl number (Pr), and the ratio of pipe diameter by particle size (D/d_p). A multiple linear regression model is used and analysed statistically using the experimental heat transfer data. The coefficients of the proposed regression model are determined by the method of least squares, which yields the following correlation giving the best fit with the present experimental data

$$Nu_s = 0.0138\mathrm{Re}_s^{0.772}\mathrm{Pr}_s^{0.809}(D/d_p)^{0.042} \tag{8}$$

where $4{,}000 \leq Re_s \leq 11{,}000$, $3.8 \leq \mathrm{Pr}_s \leq 5.0$, $102 \leq D/d_p \leq 615$.

Table 3 shows the empirical heat transfer correlations of liquid-solid suspension flow in other studies. Salamone and Newman (1955) obtained the heat transfer correlation in liquid-solid suspension flow with Reynolds number ranging from 14,000 to 140,000 with the ratio of pipe diameter by particle diameter (D/d_p) ranging from 282 to 10,500. Harada et al. (1985) obtained the heat transfer correlation with Reynolds number ranged from 8,000 to 50,000 with the ratio of pipe diameter by particle diameter ranging from 14 to 417. Ozbelge and Somer (1994) obtained the heat transfer correlation with Reynolds number ranging from 27,000 to 120,000, with the ratio of pipe diameter by particle diameter ranging from 182 to 512. The dimensionless variables Nu_s Re_s and Pr_s used in the correlation are as follows.

$$Nu_s = h_s D_i / k_s,\ Re_s = D_i u_s \rho_s / \mu_s,$$
$$\mathrm{Pr}_s = C_{ps}\mu_s / k_s \tag{9}$$

The viscosity, thermal conductivity and heat capacity are calculated using the following equations (Landau and Lifshitz, 1959; Gelperin and Einstein, 1971).

$$\mu_s = \mu_f(1+2.5C_s) \tag{10}$$

$$k_s = k_f\left[1+\frac{C_s(1-k_f/k_p)}{k_f/k_p+0.28(1-C_s)^{0.63(k_p/k_f)^{0.18}}}\right] \tag{11}$$

Table 3 Comparison of Empirical Heat Transfer Correlation for Liquid-Solid Two Phase Flows

References	Correlations	Comments
This study (1999)	$\frac{h_s D}{k_s} = 0.0138 Re_s^{0.772}\mathrm{Pr}_s^{0.809}(D/d_p)^{0.042}$	$3{,}000 \leq Re_s \leq 11{,}000$ $3.8 \leq \mathrm{Pr}_s \leq 5.0$ $102 \leq D/d_p \leq 615$ $0.01 \leq C_s \leq 0.1$
Salamone & Newman(1955)	$\frac{h_f D}{k_f} = 0.131\left(\frac{D u_s \rho_s}{\mu_s}\right)^{0.62}\left(\frac{Cp_f \mu_s}{k_f}\right)^{0.72}\left(\frac{k_p}{k_f}\right)^{0.05}\left(\frac{D}{d_p}\right)^{0.05}\left(\frac{Cp_p}{Cp_f}\right)^{0.36}$	$14{,}000 \leq \mathrm{Re} \leq 140{,}000$ $3.4 \leq \mathrm{Pr} \leq 12.7$ $0.53 \leq k_p/k_f \leq 583$ $282 \leq D/d_p \leq 10{,}500$ $0.09 \leq Cp_p/Cp_f \leq 0.22$ $0.002 < C_S < 0.012$
Harada et. al (1985)	$\frac{h_f D}{k_f} = 0.0161\left(\frac{D u_s \rho_s}{\mu_f}\right)^{0.88}\left(\frac{Cp_s \mu_f}{k_f}\right)^{1/3}(\mu_f/\mu_w)^{-0.14}$	$8{,}000 \leq \mathrm{Re} \leq 50{,}000$ $0.01 \leq C_S \leq 0.1$ $14 \leq D/d_p \leq 417$
Ozbelge & Somer(1994)	$\frac{h_s D}{k_s} = 0.202 Re_s^{0.6}\mathrm{Pr}_s^{0.675}(D/d_p)^{0.092}(\mu_s/\mu w)^{-1.95}$	$27{,}000 \leq Re \leq 120{,}000$ $2.1 \leq \mathrm{Pr} \leq 3.4$ $182 \leq D/d_p \leq 512$ $0.005 \leq C_s \leq 0.03$ $1.17 \leq \mu_s/\mu_w \leq 1.83$

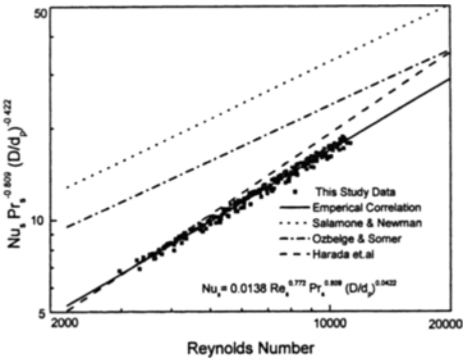

Fig. 6 Comparison of the experimental results and empirical correlations in the Nusselt numbers of liquid-solid suspension flows

$$C_{ps}=[C_sC_{pp}\rho_p+(1-C_s)C_{pf}\rho_f]/[C_s\rho_p+(1-C_s\rho_f)] \tag{12}$$

Figure 6 shows the comparison of the experimental results and empirical correlations in the Nusselt numbers of liquid-solid suspension flows. The proposed heat transfer correlation in this study is in good agreement with the correlation equation proposed by Harada et al. (1985), but some discrepancy has been noted with others. It is due to the differences in the range of the experimental parameters such as Reynolds number, particle size and material, and solid concentration.

4.3 Pressure drop measurement

Figure 7 shows the experimental results of pressure drop between the inlet and outlet in the horizontal pipe at the particle size of 13μm in mass median diameter. The pressure drop for clear water is about 3,000 Pa/m at the flow velocity of 1m/s and that for 50% solid concentration is 16,000 Pa/m at the flow velocity of 1m/s. The total pressure drop in the two phase transportation is the sum of the pressure due to water only and the additional drop due to the particles, so it increases with particle concentration.

Figure 8 shows the pressure drop measurement of the heat exchanger as a function of solid concentration at the Reynolds number of 10,700 and particle sizes in the pipe mean velocity of 1m/s. The measured pressure drop increases by about 55% at the particle volume concentration of 10%, and shows no dependence on particle size. For the higher solid volume concentrations the pressure drop still increases, whereas the heat transfer decreases. The increase in the pressure drop with high solids concentrations may be attributed to stronger particle-particle interaction. This interaction results in the decrease of heat transfer coefficients.

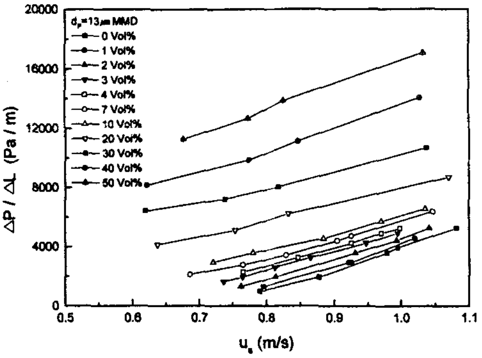

Fig. 7 Pressure drop measurement of the heat exchanger as a function of solid concentration and flow velocity at the particle diameter of 13μm

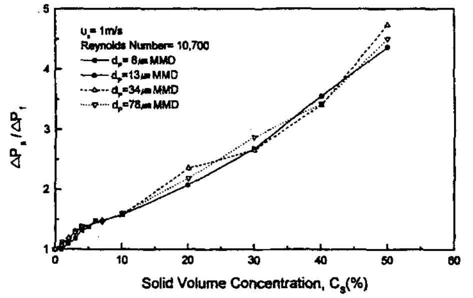

Fig. 8 Pressure drop measurement of the heat exchanger as a function of solid concentration at the Reynolds number of 10,700

5. Conclusions

The effects of solid particles on the heat transfer and pressure drop in a liquid-solid suspension flow are investigated experimentally using the double pipe heat exchanger. The experiments are carried out using the spherical fly ash particles ranging from 4 to 78μm in mass median diameter. The volume concentration of solids in the slurry ranging from 0 to 50% and Reynolds number ranging from 4,000 to 11,000. The results can be summarized as follows:

(1) The heat transfer coefficient increases with particle volume concentration exhibiting the highest heat transfer enhancement at the 3% solid volume concentration and then gradually decreases. The presence of the solids leads to an increase in the heat transfer rate up to 25% for solid volume concentration around 3% and the particle size of 13μm. It may be attributed to modifications of pipe flow turbulence due to liquid-solid interaction.

(2) The heat transfer ratio showed a tendency to increase with decreasing particle size but there is no increase of heat transfer below the particle size of 13μm.

(3) The heat transfer correlation of liquid-solid suspension flow is derived using the dimensional analysis with suspension properties; $Nu_s = 0.0138 Re_s^{0.772} \mathrm{Pr}_s^{0.809} (D/d_p)^{0.042}$.

(4) The pressure drop of liquid-solid suspension flow is found to increase with particle concentration and shows no dependence on the particle size. The pressure drop increased by about 55% at 10% particle volume concentration. For higher solid volume concentrations the pressure drop still increased, whereas the heat transfer decreased.

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