Heat-Transfer Coefficient in Viscous Liquid–Solid Circulating Fluidized Beds

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Introduction

Because of unique features, such as effective solid–liquid contact and high rates of heat and mass transfer, liquid–solid fluidized beds have been widely adopted for catalytic liquid-phase reactions, separation, and recovery of materials with ion-exchange resin, adsorption, sedimentation, and wastewater treatment (Fan, 1989). However, the use of conventional liquid–solid fluidized beds has been restricted, when the fluidized solid particles are small or porous and their density is small, because they must be operated at a liquid velocity lower than the terminal velocity of the particles. Moreover, in beds of viscous liquid medium, the available range of liquid velocity becomes considerably narrower because of the substantial decrease of terminal velocity of fluidized solid particles, which is often encountered in practical applications.

To overcome this disadvantage in using a liquid–solid fluidized bed, the circulation mode of solid particles has been used (Cho et al., 1999, 2001a,b; Kuramoto et al., 1998, 1999; Liang et al., 1996; Zheng et al., 1999, 2000, 2001). It has been well established that a liquid–solid circulating fluidized bed can be used with high liquid velocity to increase the production or operation efficiency per unit cross-sectional area of the column. In addition, the liquid–solid circulating fluidized bed can minimize the dead zone and increase the contacting efficiency between the particles and the continuous liquid medium by enhancing the shear stress at the interface between the two phases.

In spite of reports of some studies dealing with the hydrodynamic characteristics of liquid–solid circulating fluidized beds (Cho et al., 2005; Kuramoto et al., 1998, 1999; Liang et al., 1996; Zheng et al., 1999), there has been little information on the heat transport phenomena that characterize them. Kuramoto et al. (1999) measured the fluctuations of voidage and heat-transfer coefficient to analyze the particulate and aggregative fluidization in the riser of a liquid–solid circulating fluidized bed. However, they used only one kind of particle in the water. For practical applications of liquid–solid circulating fluidized beds, relevant information on the heat transfer in the riser with viscous liquid medium is essential because the temperature in the reactor or process has to be controlled effectively in spite of complicated viscous liquid–solid contacting.

Thus, in the present study, the overall heat-transfer coefficient has been obtained in liquid–solid circulating fluidized bed with viscous liquid medium. The heat-transfer resistance between the immersed heater and the bed proper of the riser has been discussed based on the two resistances–in–series model. Effects of liquid velocity (0.16–0.44 m/s), particle size (1.0, 1.7, 2.1, and 3.0 mm), solid circulation rate (2.0–8.0 kg m^{-2} s^{-1}), and liquid viscosity (1.0–38.9 mPa·s) on the overall heat-transfer coefficient and resistances for heat transfer in the bed have been determined.

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Table 1. Liquid Physical Properties and Operating Conditions

Substance	$\mu_{L,app}$ (mPa · s)	$\sigma_L \times 10^3$ (N/m)	ρ_L (kg/m^3)	$U_L \times 10^2$ (m/s)	$d_P \times 10^3$ (m)
Pure water	0.96	72.9	1000	15–45	1.0–3.0
CMC 0.1 wt %	11	73.2	1001	15–45	1.0–3.0
CMC 0.2 wt %	24	73.3	1002	15–45	1.0–3.0
CMC 0.3 wt %	38	73.6	1003	15–45	1.0–3.0

Experimental Studies

Experiments were carried out in the riser of a liquid–solid circulating fluidized bed, composed of three main sections: the riser column, liquid–solid separator, and solid-recycle device. The diameter and height of the riser were 0.102 m ID and 3.5 m, respectively. A detailed description of this experimental system can be found elsewhere (Cho et al., 2001a,b, 2003). The solid particles were returned to the bottom of the riser through the solid-recycle device. The solid circulation rate was determined by measuring the amounts of solid accumulated above the butterfly valve in the solid-recycle device (Cho et al., 1999, 2001a,b; Kim et al., 1999). As a heating source, a cone-shaped heater with an outside diameter of 0.03 m and a length of 3.0 m was placed coaxially on the distributor plate at the center of the riser. To maintain the isothermal condition at the heater surface, the heater was constructed from a copper rod, axially drilled to accommodate a cartridge heater. Four 1.0-mm-diameter iron–constantan thermocouples were mounted in 2.0-mm wells and soldered in place, flush with the heater surface, to measure the temperature at the heater surface. Four thermocouples (iron–constantan, J-type) were positioned 90° apart at the elevation of 0.3-m intervals from the inlet of the solid-recycle system. Five iron–constantan thermocouples were installed radially 0.5 m above the particle recycle port to measure the radial temperature profile in the riser. The location of the first thermocouple was 0.005 m from the immersed heater surface; the second through fifth thermocouples were placed at the radial intervals of 0.005, 0.010, 0.020, and 0.021 m, respectively. These thermocouples were connected to a digital thermometer, data acquisition system (Data Precision Model DT 3001), and a personal computer to record temperatures, simultaneously and continuously, at all points.

Individual holdups of solid and liquid phases were measured by means of a static pressure drop method with the knowledge of pressure drop in the section (Cho et al., 2001a,b; Kang et al., 1958).

Glass beads, with a diameter of either 1.0, 1.7, 2.1, or 3.0 mm and a density of 2500 kg/m^3, served as the fluidized particles; tap water or an aqueous solution of carboxymethylcellulose (CMC) served as the viscous liquid medium. The apparent viscosity of the liquid medium was determined with a Brookfield Synchrolectric Rotational Viscometer (Cho et al., 2002) because in liquid–solid fluidized beds, the shear rate of CMC solutions did not undergo any significant changes with variations of operating variables within the experimental conditions. The liquid properties and operating conditions are listed in Table 1. When a steady state was reached, the temperatures were measured repeatedly. The heat transfer coefficient was calculated as

$$h = \frac{Q}{A(\overline{T_h - T_m})} \tag{1}$$

where Q is the heat flux from the heater surface to the riser; A is the effective surface area of the heater; and T_h and T_m are the temperature of the heater surface and the mean temperature of the riser, respectively. The heat flux was obtained from the DC power supplier and the temperature difference between the immersed heater and the riser was determined by (Chiu and Ziegler, 1983; Kang et al., 1988, 1991)

$$\overline{T_h - T_m} = \frac{\int_0^R u(r)[T_h - T(r)]rdr}{\int_0^R u(r)rdr} \tag{2}$$

The heat flux Q was verified from the energy balance

$$Q = \dot{m}C_{pL}(T_{mo} - T_{mi}) \tag{3}$$

where $\dot{m}$ and C_{pL} are the mass flow rate and specific heat of the liquid phase, respectively; and T_{mo} and T_{mi} are the outlet and inlet temperatures, respectively.

Results and Discussion

Overall heat transfer coefficient

A typical example of solid holdup in the riser of a liquid–solid circulating fluidized bed can be seen in Figure 1. In this figure, the solid holdup increases gradually with increasing

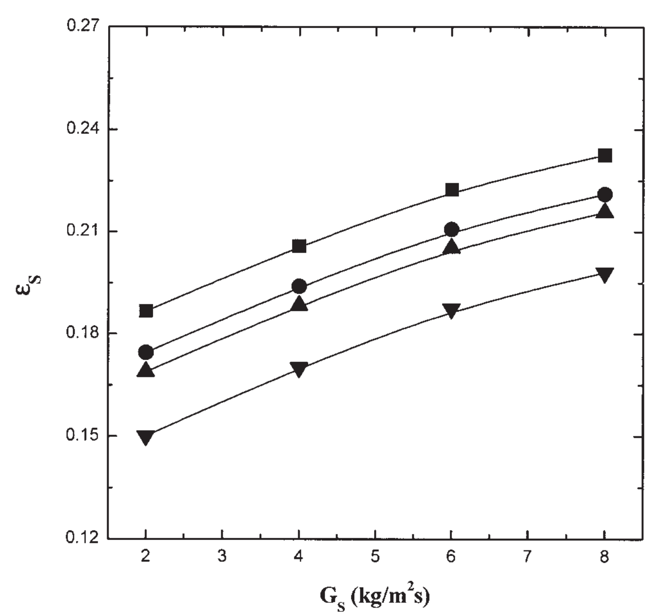

Figure 1. Effects of solid circulation rate on the solid holdup in the riser of liquid–solid circulating fluidized beds (U_L = 0.24 m/s, d_P = 1.7 mm).

$\mu_{L,[infi]app}$ (mPa·s): ■ 0.96, ● 24, ▲ 11, ▼ 38.

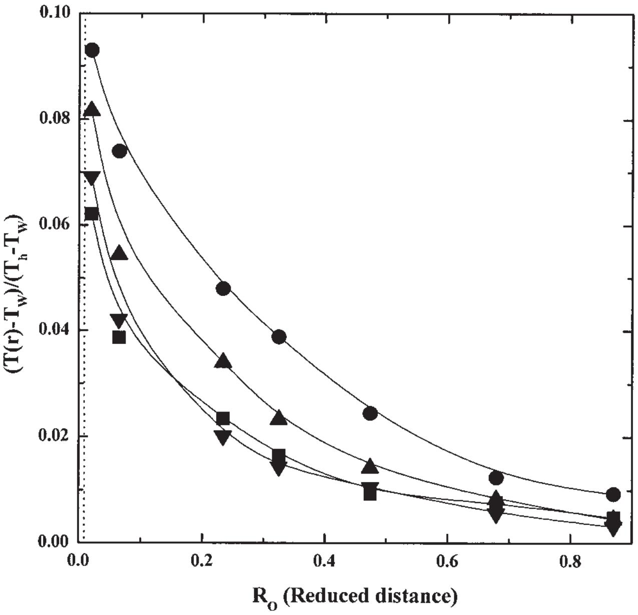

Figure 2. Typical radial temperature profile in the riser of liquid–solid circulating fluidized beds.

$U_L\times 10^2$ (m/s): ■ 19, ● 28, ▲ 24, ▼ 42; G_S (kg m^{-2} s^{-1}): ■ 2, ● 4, ▲ 4, ▼ 6; $d_P\times 10^3$ (m): ■ 1, ● 2.1, ▲ 1.7, ▼ 3; $\mu_{L,[infi]app}$ (mPa·s): ■ 0.96, ● 24, ▲ 11, ▼ 38.

solid circulation rate (G_S), but decreases with increasing liquid viscosity. It has been observed that the variation of solid holdup with bed height is considerable when the liquid velocity is relatively low; however, when the liquid velocity is relatively high enough to circulate the solid particles, the value of ε_S does not significantly change with bed height (Cho et al., 2001a,b, 2005; Kim et al., 1999).

A typical radial temperature profile in the riser of the liquid–solid circulating fluidized bed can be seen in Figure 2, from which the mean temperature difference between the heater surface and the bed proper has been determined by means of Eq. 2.

The heat-transfer coefficient from the immersed heater surface to the bed proper in the riser of a liquid–solid circulating fluidized bed can be seen in Figure 3, with the variations of liquid velocity and fluidized particle size. In this figure, the values of heat-transfer coefficient in the riser with fluidized solid particles have been compared with those in the solid-free system at the same liquid flow rate. As can be seen, the addition of solid particles in the bed can effectively increase the h value. The effects of fluidized particles on h increase with increasing size of solid particles. The value of heat-transfer coefficient decreases only slightly with increasing flow rate of the viscous liquid medium. It has been well established that the holdup of particles tends to decrease with increasing liquid velocity in a given solid circulation rate and particle size (Cho et al., 2001 a,b; Kim et al., 1999), which leads to the decrease of turbulence arising from fluidized particles. However, the increase of liquid velocity results in the increase of liquid turbulence. Because of these competing effects on the heat transfer coefficient, the h value dose not significantly change but decreases only slightly with increasing U_L. The effects of decreasing solid holdup may be preferred to those of increasing turbulence on the h value in this system, with increasing U_L. It is interesting to compare these results with those in the conventional liquid–solid fluidized beds; the value of h increases and exhibits a local maximum with increasing U_L but it decreases profoundly with a further increase of U_L, in the conventional liquid–solid fluidized beds. It has been established that this is attributed to the significant decrease in the solid holdup at the higher U_L range (Fan, 1989; Kang et al., 1985; Kim and Kang, 1997). It seems that the effects of U_L on the h value are strongly dependent on the characteristics of the fluidizing system. On the other hand, the value of heat-transfer coefficient increases with increasing particle size in all the cases studied (Figure 3). This can be attributable to the effective motion of fluidized particles for the heat transfer in the viscous liquid medium with increasing particle size. It has been pointed out that the larger particles can have a larger inertial force to move and generate the turbulence in the viscous liquid medium (Kang et al., 1985, 1991; Kato et al., 1981).

Figure 4 shows the effects of solid circulation rate on the heat-transfer coefficient in the riser of the liquid–solid circulating fluidized bed. As can be seen in this figure, the h value increases gradually with increasing G_S. Note that the solid holdup increases with increasing G_S, as depicted in Figure 1 (Cho et al., 2001a,b; Kuramoto et al., 1998). The increase of solid holdup, in turn, results in the increase of turbulence in the bed. In other words, the turbulence in the bed increases with increasing solid circulation rate by disturbing the upward liquid flow by means of hindrance effects of fluidized solid particles. Moreover, the contacting frequency between the heater surface and the fluidized particles would increase with increasing solid holdup or solid circulation rate in the region adjacent to the heater surface. This can be effective for heat transfer from the heater surface to the fluidized bed proper. Compared with the

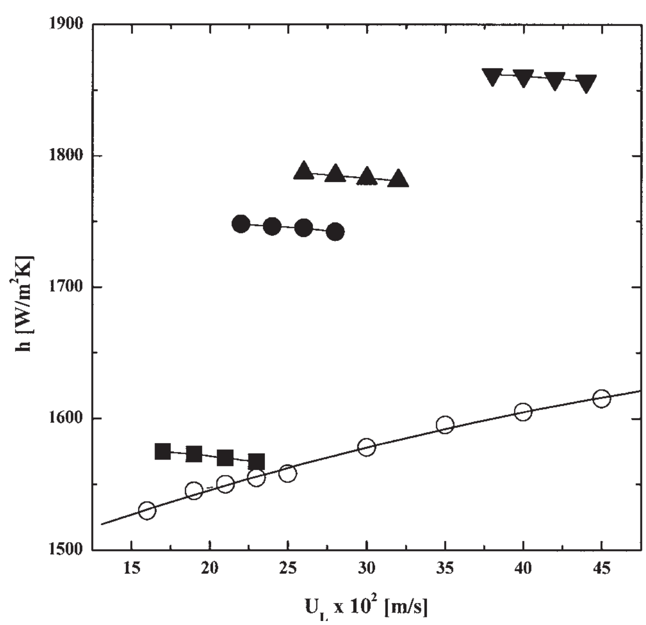

Figure 3. Effects of U_L on the heat-transfer coefficient in the riser of liquid–solid circulating fluidized beds ($\mu_{L,[infi]app}$ = 24 mPa·s, G_S = 2 kg m^{-2} s^{-1}).

$d_P\times 10^3$ (m): ○ 0, ■ 1, ● 1.7, ▲ 2.1, ▼ 3.

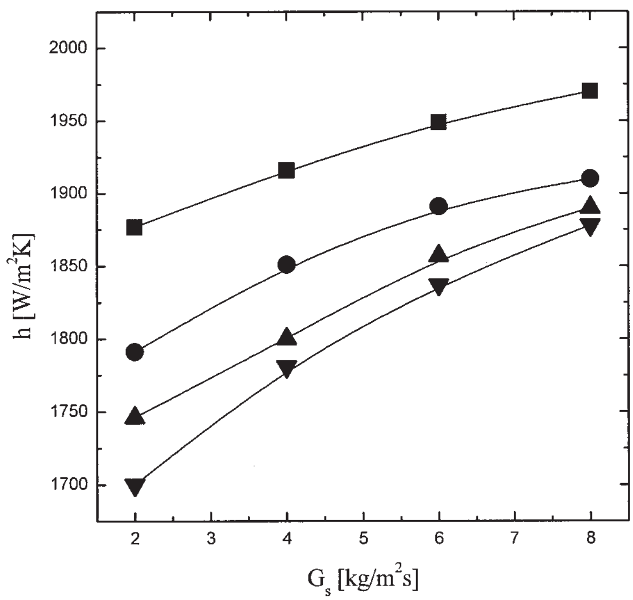

Figure 4. Effects of G_S on the heat-transfer coefficient in the riser of liquid–solid circulating fluidized beds (d_P = 1.7 mm, U_L = 0.24 m/s).

$\mu_{L,\mathrm{[infi]app}}$ (mPa·s): ■ 0.96, ● 11, ▲ 24, ▼ 38.

conventional liquid–solid fluidized beds, the value of h can be substantially enhanced by increasing G_S in the liquid–solid circulating fluidized bed, especially at the higher μ_L range (Figure 4).

The heat-transfer coefficient decreases with increasing viscosity of the liquid medium, as can be seen in Figure 5. It has been reported that the increasing viscosity of a liquid medium can decrease the mobility of the particles in the bed, which results in the decrease of turbulence in the bed and in turn results in the decrease of heat-transfer coefficient between the immersed heater and the bed proper (Fan, 1989; Kang et al., 1985).

In the conventional liquid–solid fluidized beds with viscous liquid medium, the values of minimum fluidization velocity and terminal velocity of particles noticeably decrease because of the increase of drag force acting on the fluidized particles; thus, the value of solid holdup also substantially decreases in a given U_L. The decrease of solid holdup results in the decrease of contacting frequency directly at the heater surface, thus consequently resulting in the decrease of heat-transfer coefficient, as mentioned earlier. However, the value of h can be noticeably increased by increasing G_S by using the solid circulation mode, even in the relatively higher viscous liquid medium (Figure 5).

Heat transfer resistance and thickness of region adjacent to the heater surface

It has been generally observed and understood that the radial temperature profile in the region adjacent to the heater surface is much steeper than that in the bed proper in the conventional liquid–solid fluidized beds (Chiu and Ziegler, 1983; Kang and Kim, 1988; Kang et al., 1991). In the riser of the liquid–solid circulating fluidized bed, a similar trend of temperature profile in the radial direction can also be found (Figure 2). From the radial temperature profile, it is apparently recognized that two resistances are connected in series for the transportation of heat from the heater surface to the bed proper, as in the case of conventional liquid–solid fluidized beds (Kang and Kim, 1988; Kang et al., 1991; Kim and Kang, 1997; Muroyama et al., 1986). Based on this two resistances–in–series model, the overall heat transfer resistance can be expressed as

$$\frac{1}{h} = \frac{1}{h_h} + \frac{1}{h_b} \tag{4}$$

where h, h_h, and h_b are the overall heat-transfer coefficient, heat-transfer coefficient in the region adjacent to the heater surface and that in the bed proper, respectively. The value of h_h can be obtained from the heat balance around the heater surface (Kang and Kim, 1988; Kang et al., 1991), by means of the following equation

$$h_h = \frac{Q}{(T_h - T_\delta)A} \tag{5}$$

where T_h and T_δ are the temperatures of the heater surface and region around it, respectively. The value of T_δ has been determined by extrapolating the radial temperature profile to the heater surface by means of the finite-difference method (Kang et al., 1991; Muroyama et al., 1986; Patel and Simpson, 1977) because the region adjacent to the heater surface is essentially a very thin liquid film around the heater (Chiu and Zieagler, 1983; Wasmund and Smith, 1967).

It is understood that the h_h can be directly related to the thickness of liquid thin film around the heater surface δ, as in Eq. 6, because the steady-state heat conduction may take place

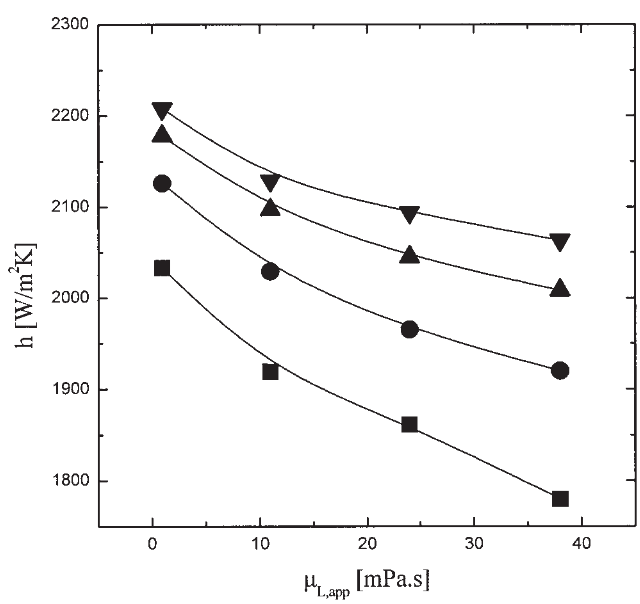

Figure 5. Effects of $\mu_{L,\mathrm{[infi]app}}$ on the heat-transfer coefficient in the riser of liquid–solid circulating fluidized beds (d_P = 3 mm, U_L = 0.40 m/s).

G_S (kg m^{-2} s^{-1}): ■ 2, ● 4, ▲ 6, ▼ 8.

in the very thin liquid layer (Kang et al., 1991; Lewis et al., 1982)

$$h_h = \frac{k_L}{\delta} \tag{6}$$

In Eq. 6, k_L is the thermal conductivity of the liquid phase. After determining h_h from Eq. 5 with the knowledge of T_h and T_δ, the value of δ has been determined from Eq. 6 (Kang et al., 1991; Wasmund and Smith, 1967).

Effects of liquid velocity, particle size, solid circulation rate, and liquid viscosity on the liquid film thickness adjacent to the heater surface can be seen in Figure 6. Note that the δ value does not significantly change with variation of liquid velocity, whereas it substantially decreases with increasing particle size (Figure 6a). As mentioned earlier, the effects of velocity of continuous liquid medium on the thickness of thin liquid film adjacent to the heater surface would be marginal because of the competing effects of the increase of turbulence and decrease of solid holdup in the bed. However, the larger particles would have a greater potential of eroding the thin liquid film around the heater surface by more effective contacting between the fluidized particles and the heater surface. The thickness of the thin liquid film δ decreases gradually with increasing solid circulation rate because of the increase of contacting frequency between the fluidized particles and the heater surface by increasing the solid holdup in the bed (Figures 1 and 6b). In conventional liquid–solid fluidized beds, the value of δ decreases with increasing solid holdup in the beds (Kang et al., 1991). Effects of liquid viscosity on the δ value can be seen in Figure 6c. In this figure, the value of δ increases with increasing liquid viscosity. This can be the main reason why the heat-transfer coefficient decreases with increasing viscosity of the continuous liquid medium (Figure 5) (Fan, 1989; Kang et al., 1985; Kim and Kang, 1997; Kim et al., 1986). The adhesion force of liquid medium to the heater surface increases with increasing viscosity of the liquid phase, and thus the value of δ would increase with increasing liquid viscosity in a given operating condition. In addition, the mobility of fluidized solid particles would noticeably decrease with increasing liquid viscosity, which consequently results in the decrease of frequency as well as intensity of contacting between the heater surface and the fluidized particles. Also, the overall flow may move from turbulent to laminar as the viscosity is increased, especially at the lower U_L and higher $\mu_{L,app}$ conditions. Therefore, the value of δ increases with increasing liquid viscosity.

The value of heat-transfer resistance in the fluidized bed proper, $1/h_b$, was obtained by Eq. 4, from the known values of h and h_h. Effects of operating variables such as liquid velocity, particle size, solid circulation rate, and liquid viscosity on the heat-transfer resistance in the bed proper can be seen in Figure 7. Note in Figure 7a that the heat-transfer resistance in the bed proper does not significantly change, but increases only slightly, with increasing liquid velocity. However, the resistance decreases gradually with increasing G_S, whereas it increases with increasing liquid viscosity (Figures 7b and c). The reasons for variation of $1/h_b$ with operating variables can be mainly attributed to the variations of the holdup and mobility of fluidized solid particles in the riser. That is to say, the solid holdup increases with increasing d_P or G_S but it decreases with

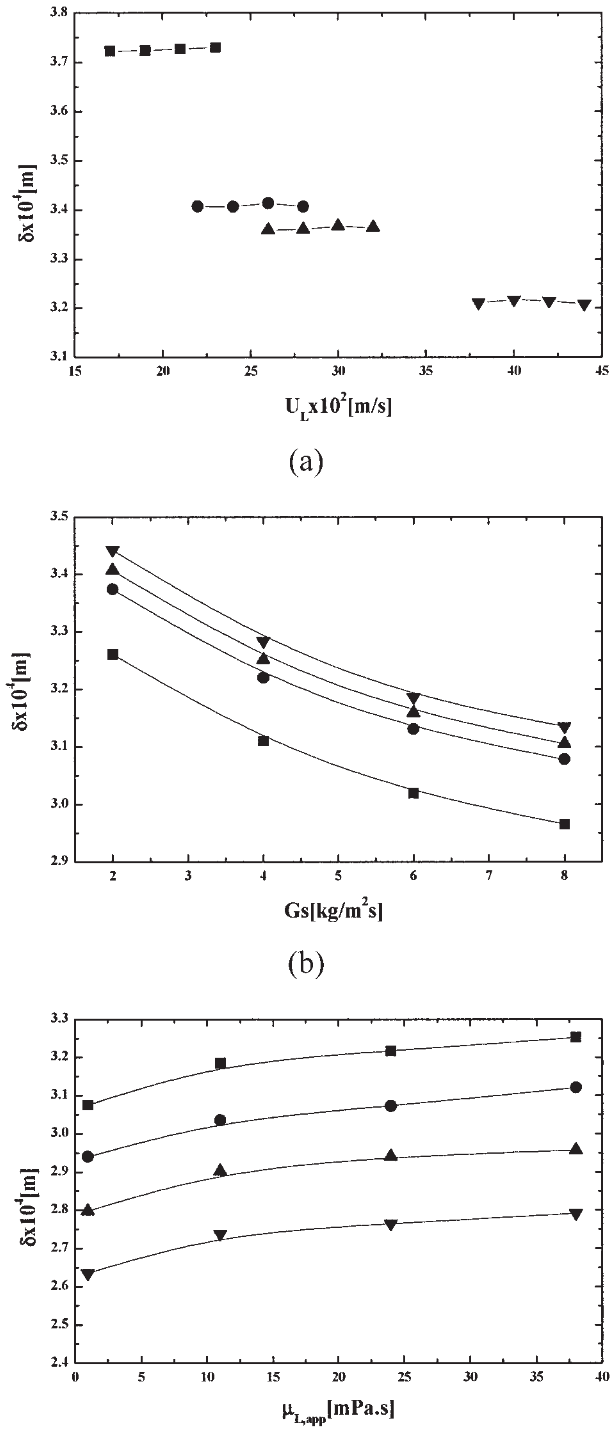

Figure 6. Effects of U_L, G_S, and $\mu_{L,\text{[infi]app}}$ on δ in the riser of liquid–solid circulating fluidized beds.

(a) G_S = 2 kg m^{-2} s^{-1}, $\mu_{L,\text{[infi]app}}$ = 24 mPa·s: ■ d_P = 1 mm, ● d_P = 1.7 mm, ▲ d_P = 2.1 mm, ▼ d_P = 3 mm; (b) U_L = 0.24 m/s, d_P = 1.7 mm: ■ $\mu_{L,\text{[infi]app}}$ = 0.96 mPa·s, ● $\mu_{L,\text{[infi]app}}$ = 11 mPa·s, ▲ $\mu_{L,\text{[infi]app}}$ = 24 mPa·s, ▼ $\mu_{L,\text{[infi]app}}$ = 38 mPa·s; (c) U_L = 0.4 m/s, d_P = 3 mm: ■ G_S = 2 kg m^{-2} s^{-1}, ● G_S = 4 kg m^{-2} s^{-1}, ▲ G_S = 6 kg m^{-2} s^{-1}, ▼ G_S = 8 kg m^{-2} s^{-1}.

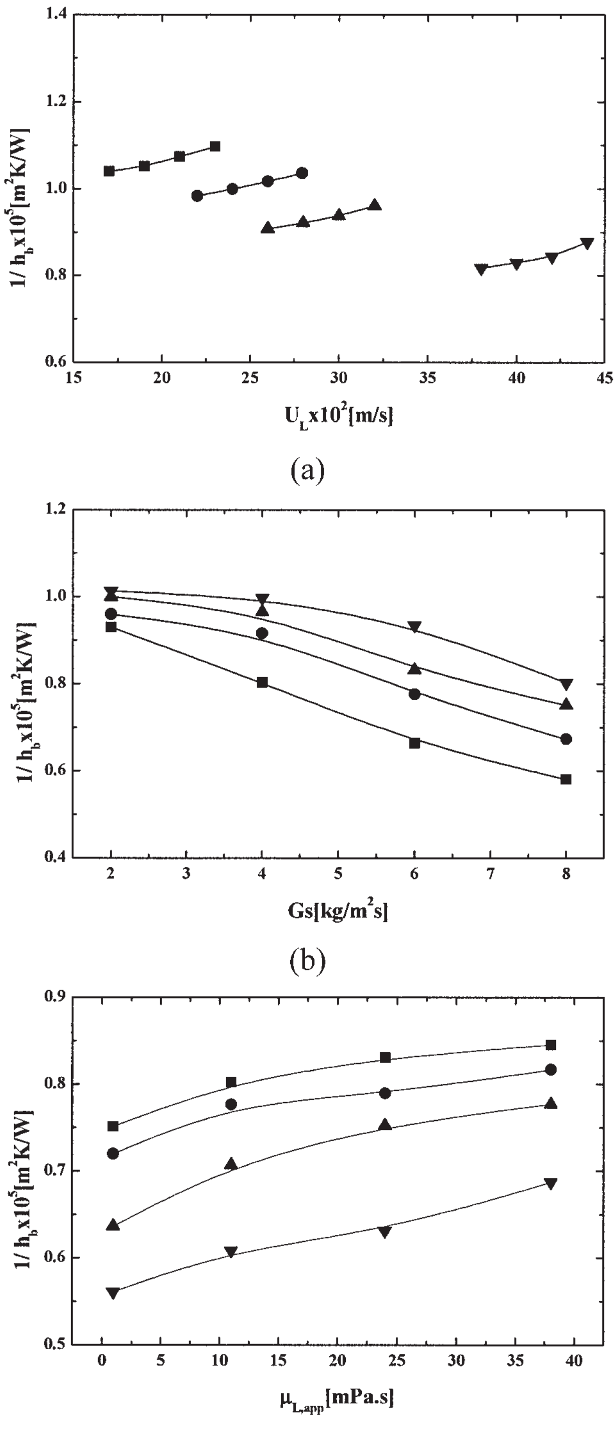

Figure 7. Effects of U_L, G_S, and $\mu_{L,[infi]app}$ on $1/h_b$ in the riser of liquid–solid circulating fluidized beds.

Symbols and values for (a), (b), and (c) are the same as those in Figure 6.

increasing U_L or liquid viscosity (Cho et al., 2005; Kim et al., 1999). Thus, as in the case in the region adjacent to the heater surface, the heat-transfer resistance in the bed proper decreases with increasing solid holdup and its mobility. However, the heat-transfer resistance in the region adjacent to the heater surface has been preferred to that in the bed proper, to determine the overall heat transfer resistance and thus heat-transfer coefficient in the riser.

Correlation of heat-transfer coefficient

The heat-transfer coefficient in the region adjacent to the heater surface has been well correlated in terms of the modified Colburn j-factor $j_{H,h}$, containing the liquid flow rate and bed porosity as a function of modified Reynolds number Re_M, given that the heat-transfer coefficient strongly depends on these factors in conventional liquid–solid fluidized beds (Kang et al., 1991; Muroyama et al., 1986). In the liquid–solid circulating fluidized bed, the values of the modified Colburn j-factor, based on h_h obtained in this study, have also been well correlated as a function of the modified particle Reynolds number as

$$j_{H,h} = 0.0632\ \mathrm{Re}_M^{-0.184} \tag{7}$$

The relation of Eq. 7 is generally well fitted with the experimental results with a correlation coefficient of 0.98 and is comparable with other relations obtained from the conventional liquid–solid fluidized beds (Kang et al., 1991; Kim and Kang, 1997; Muroyama et al., 1986; Simpson and Patel, 1973). The values of the modified Colburn j-factor, based on the overall heat-transfer coefficient j_H, have also been well correlated as a function of the modified Reynolds number, as in Eq. 8, with a correlation coefficient of 0.96. The covered range of Re_M in Eqs. 7 and 8 is $16.44 \leq \mathrm{Re}_M \leq 9027$

$$j_H = 0.0549\ \mathrm{Re}_M^{-0.224} \tag{8}$$

Concluding Remarks

The immersed heater-to-bed heat-transfer coefficient in the riser of a liquid–solid circulating fluidized bed increases with increasing solid circulation rate because the solid holdup increases with increasing G_S. The value of heat-transfer coefficient decreases only slightly with increasing velocity of the viscous liquid medium at the relatively higher range of U_L. The heat-transfer coefficient increases with increasing particle size but decreases gradually with increasing liquid viscosity.

The heat-transfer resistance in the riser of liquid–solid circulating fluidized bed has been well analyzed by adapting the two resistances–in–series model. The thickness of liquid thin film around the heater surface (δ) does not significantly change with increasing liquid velocity, but decreases with increasing solid circulation rate, while gradually increasing with increasing liquid viscosity. The heat-transfer resistance in the bed proper decreases with increasing G_S, but increases with increasing liquid viscosity, while only slightly increasing with U_L. The heat-transfer resistance in the region adjacent to the heater surface has been dominant for the determination of overall heat transfer coefficient in the bed.

Acknowledgments

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Notation

A = surface area of heater, m^2
C_{pL} = specific heat of the liquid phase, J kg^{-1} K^{-1}
D = column diameter, m
d_P = particle size, mm
G_S = solid circulation rate, kg m^{-2} s^{-1}
h = heat-transfer coefficient, W m^{-2} K^{-1}
h_b = heat-transfer coefficient in the bed proper, W m^{-2} K^{-1}
h_h = heat-transfer coefficient in the region adjacent to the heater, W m^{-2} K^{-1}
j_H = modified Colburn j-factor, $(h/\rho_L C_{pL} U_L)\varepsilon_L \mathrm{Pr}^{2/3}$
$j_{H,h}$ = modified Colburn j-factor in the region adjacent to the heater, $(h_h/\rho_L C_{pL} U_L)\varepsilon_L \mathrm{Pr}^{2/3}$
k_L = thermal conductivity of liquid phase, W m^{-1} K^{-1}
$\dot{m}$ = mass flow rate of liquid phase, kg/s
Pr = Prandtl number, $C_{pL}\mu_{L,app}/k_L$
Q = heat flow rate, W
Re_M = modified Reynolds number, $d_P U_L \rho_L/\mu_{L,app}(1 - \varepsilon_L)$
T_b = temperature in the bed proper, K
T_h = temperature at the heater surface, K
T_m = mean temperature, K
t = time, s
U_L = liquid velocity, m/s
$U(r)$ = radial liquid velocity profile, m/s

Greek letters

ε_L = liquid hold up
ρ_s = particle density, kg/m^3
$\mu_{L,app}$ = apparent liquid viscosity, mPa·s

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