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Solid Circulation Characteristics in an Internally Circulating Fluidized Bed with Orifice-Type Draft Tube

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Abstract−Effects of superficial gas velocities to a draft tube, to an annulus section and particle size on the solid circulation rate (G_s) have been determined in an internally circulating fluidized bed (0.28 m I.D.×2 m high) with an orifice type draft tube. The solid circulation rate from the draft tube to an annulus section increases with increasing gas velocities to the draft tube (U_d) and annulus section (U_a) and consequent increase in pressure drop across the orifice (ΔP_{or}). However, the values of G_s decrease by 7-21% with increasing particle size from 86 to 288 μm. The pressure drop across the orifice increases with increasing U_d and U_a. However, ΔP_{or} decreases by 5-23% with increasing particle size. To predict G_s in an internally circulating fluidized bed, a correlation is proposed as a function of ΔP_{or}.

Key words: Internally Circulating Fluidized Bed, Draft Tube, Solid Circulation Rate, Pressure Drop across the Orifice, Correlation

INTRODUCTION

Circulating fluidized beds (CFBs) have been studied [Kim et al., 2001, 2002; Kang et al., 1999; Namkung et al., 1999; Cho et al., 1996] and widely used as industrial reactors, but they require very tall main vessels as a solid riser and accompanying tall cyclones. Therefore, internally circulating fluidized bed reactors (ICFBs) have been developed to circumvent the conventional CFB reactors to reduce the height and consequent reduction of construction cost. In an ICFB, a draft tube or a flat plate has been used to divide the bed for internal solid circulation within a single vessel. Particles are always transported upward in the draft tube and moved downwards in the annulus section. This ICFB reactor has several advantages, besides the compact size. Solid circulation rate can be easily controlled by gas supply to the draft tube and annulus sections having low particle entrainment from the reactor. Heat loss from the reactor is comparatively lower than conventional CFBs since its riser is located inside reactor and its annular bed acts as an additional refractory. Longer residence time of fine char particles in the annulus region may provide a much higher conversion level compared with conventional fluidized bed combustors or incinerators. Thus, ICFB reactors have been applied to coal combustion, coal gasification and incineration of the solid wastes [Kim et al., 2000; Mukadi et al., 1999; Lee et al., 1998; Riley and Judd, 1987; Kuramoto et al., 1986].

Since the amount and size of solid wastes are not regular in incinerators, stable operation of ICFB reactors at the different particle size is required for wide range of loads with variation of solid circulation rate. Therefore, solid circulation rate has to be determined to provide prerequisite knowledge to design the internally circulating fluidized bed incinerator. The solid circulation rate greatly affects the solid residence time, gas-solid contact, and heat and mass transfer rates.

In the present study, the effects of gas velocities to draft tube, to annulus section and particle size on the solid circulation rate have been determined. Also, the solid circulation rate has been correlated with pressure drop across the orifice.

EXPERIMENTAL

Experiments were performed in an acryl column (0.28 m I.D.×2 m high) with a centrally located draft tube (0.1 m I.D.×0.9 m high) as shown in Fig. 1. The air plenum was divided into two parts to supply gas into the orifice type draft tube having four holes (0.03 m-I.D.) and the annulus region separately. For air supply to the draft tube (0.1 m-I.D.), a distributor plate with seven bubble caps was used. Also, a conical plate with an inclined angle of 60º relative to the horizontal plane with 18 bubble caps was used for gas supply to the annulus section. This type of gas distribution is known to reduce the stagnant region at the bottom of the bed. Each tuyere has four holes (2.5 mm-I.D.), and the top of the bubble cap has an inclined angle of 45º to prevent accumulation of particles on the cap. Particles were fluidized by the compressed air through a pressure regulator, a filter and a gas flow meter. Four different sizes of sand particles (86, 120, 170 and 288 μm) were used. The bed height in the annulus was maintained at 0.86 m above the distributor for all the experimental conditions. Pressure taps were mounted flush to the wall of both the main column and draft tube that were connected to pressure transmitters to measure pressure in the bed. Pressure drop across the orifice was calculated from pressure difference between the annulus and the draft tube sections.

Solids circulation rate was determined from the particle downward velocity in the annulus bed of moving solids [Ahn et al., 1999]. As a tracer particle, the heated bed material was used to measure the particle downward velocity in the moving bed section by two

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‡This paper is dedicated to Professor Dong Sup Doh on the occasion of his retirement Korea University.

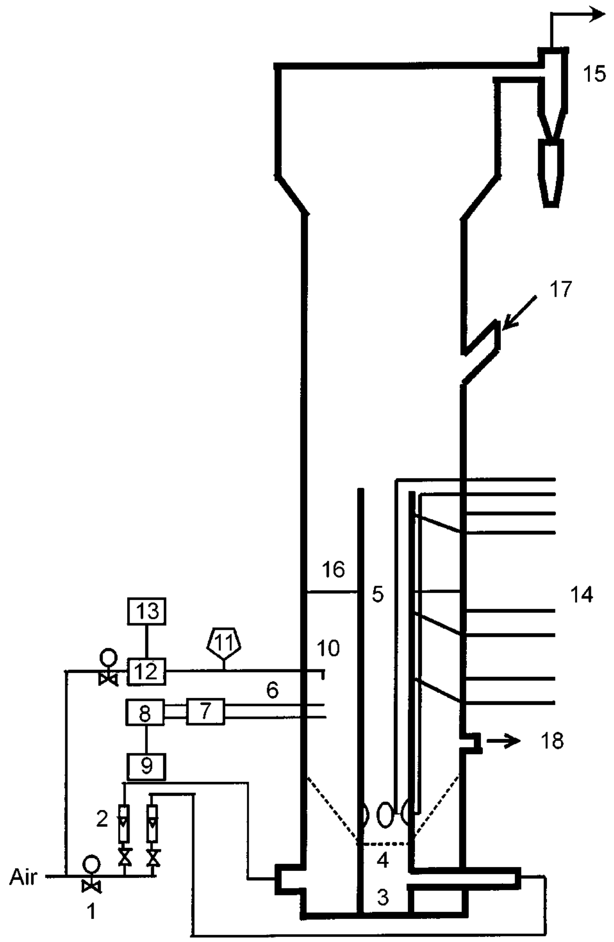

Fig. 1. Schematic diagram of experimental apparatus.

1. Pressure regulator	10. Tracer injection tube
2. Flow-meter	11. Solid hopper
3. Air box	12. Solenoid valve
4. Distributor	13. Timer
5. Draft tube	14. Pressure transmitter
6. Thermocouple	15. Cyclone
7. Bridge circuit	16. Supporter
8. Data aquisition system	17. Solid inlet
9. Personal computer	18. Solid outlet

thermistor probes at 0.51 and 0.46 m above the distributor in the annulus section. A known volume of heated sand particles was injected pneumatically by impulse into the annulus section through an L-shaped injection tube. When the heated particles were detected by the thermocouples, the response signals were stored in a personal computer through a data acquisition system. By measuring the time lag between the two peaks, the solid circulation rate can be determined.

The effects of gas velocities to the draft tube (fluidized bed, up

Table 1. Physical properties of bed material

Average particle size [μm]	86	120	170	288
Density [kg/m^3]	3,120	3,120	3,120	2,582
Minimum fluidization velocity [m/s]	0.0078	0.0150	0.0294	0.0834
Voidage at U_{mf}	0.52	0.52	0.52	0.50
Terminal velocity [m/s]	0.51	0.85	1.35	1.50

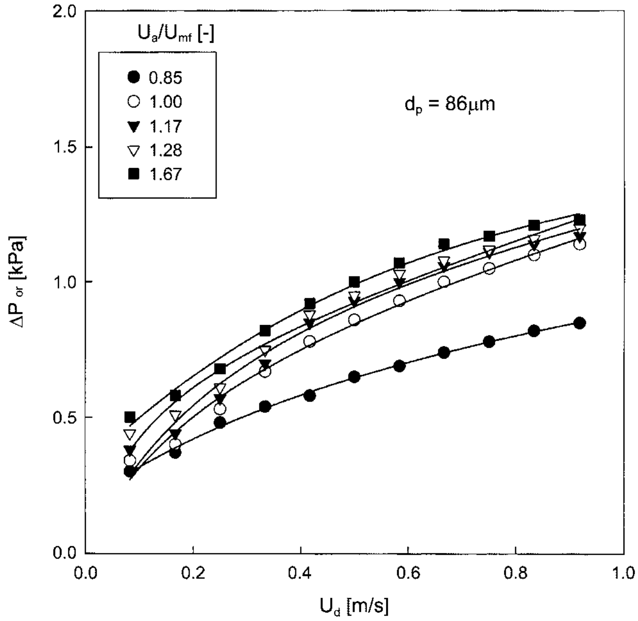

Fig. 2. Effect of U_d on ΔP_{or} with variation of U_a (d_p=86 μm).

to 1.6 m/s), to the annulus section (moving bed, up to 0.125 m/s) and particle size (86, 120, 170, 288 μm) on solid circulation rate and pressure drop across the orifices have been determined. The properties of used silica sands are listed in Table 1.

RESULTS AND DISCUSSION

1. Pressure Drop across the Orifice

The effect of U_d (0.083-0.918 m/s) on ΔP_{or} with variation of U_a/U_{mf} (0.85-1.67) is shown in Fig. 2 where ΔP_{or} increases with increasing U_d. At higher U_d, the flow regime in the draft tube was changed to the turbulent bed via the bubbling bed having low solid holdup in the draft tube, while the annulus was operated at moving bed con-

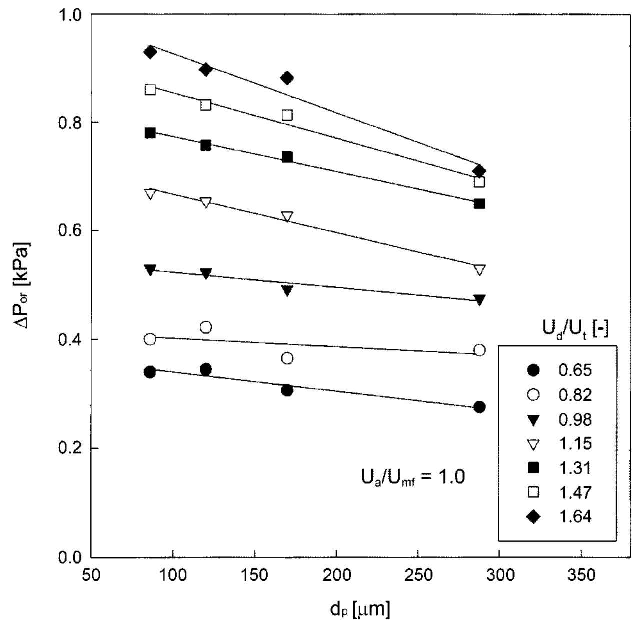

Fig. 3. Effect of particle size on ΔP_{or}.

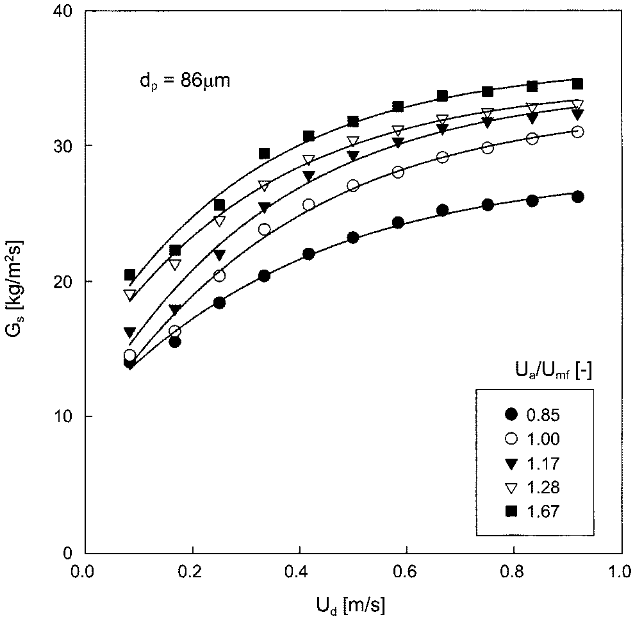

Fig. 4. Effect of U_d on G_s with variation of U_a (d_p=86 μm).

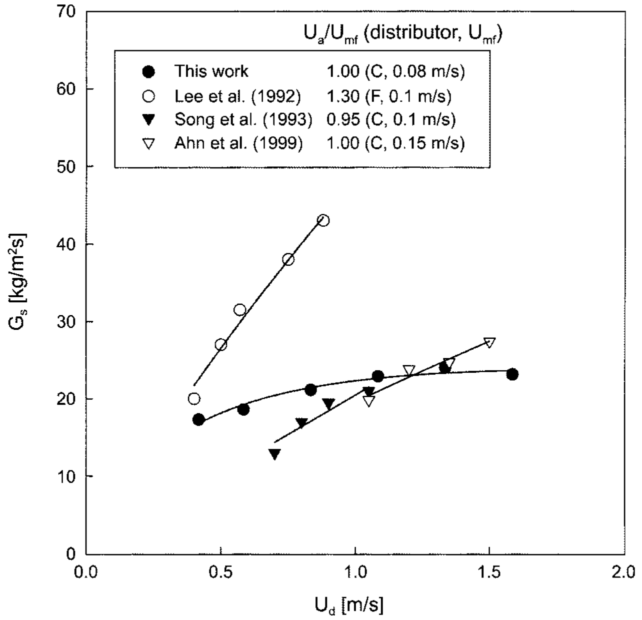

Fig. 5. Comparison of G_s at different U_a/U_{mf} (C: conical distributor, F: flat plate distributor).

dition. Therefore, both ΔP_{or} and density difference between the draft tube and annulus section increase with increasing U_d. At U_a/U_{mf} below 0.8, ΔP_{or} is rather small and increases sharply with increasing U_a/U_{mf} from 0.8 to 1.0. With increasing U_a, ΔP_{or} increases due to the increase of pressure drop in the annulus section up to the minimum fluidizing condition.

The effect of particle size (d_p; 86, 120, 170 and 288 μm) on ΔP_{or} with variation of U_d/U_t (0.65-1.64) at 1.0 U_a/U_{mf} is shown in Fig. 3. All of the particles belong to the Geldart group B particles. As the particle size is increased from 86 to 170 μm, ΔP_{or} decreases by 5-23%; whereas, ΔP_{or} increases with increasing U_d regardless of the particle size employed in this study.

2. Solid Circulation Rate

The effect of U_d (0.1-0.9 m/s) on G_s with variation of U_a (0.85-1.67U_{mf}) in the bed of 86 mm particles is shown in Fig. 4. As can be seen, G_s increase with increasing U_d due to the increase of density difference between the annulus and draft tube sections. When gas velocity in the draft tube is higher than that in the annulus section, the bed density difference between the annulus and draft tube sections increases, which may provide driving force for solids circulation in the bed [Lanauze, 1976]. As in case of ΔP_{or} (Fig. 2), G_s increase sharply at 1.0U_a/U_{mf} compared at 0.85U_a/U_{mf}. Kuramoto et al. [1986] reported that G_s depend linearly on pressure drop between the draft tube (fluidized state) and the annulus section (moving bed). In the present study, solid circulation does not occur until the gas velocity in the draft tube reaches 2U_{mf} even if the gas velocity to the annulus section is high enough. According to Choi and Kim [1991], U_d must be higher than 2.5U_{mf} for the solid circulation as found in the present study.

The experimental data of G_s in the present and previous studies [Lee et al., 1992; Song et al., 1997; Ahn et al., 1999] are compared as shown in Fig. 5. Lee et al. [1992] and Song et al. [1997] used the draft tube with the gap height type instead of orifice type and Lee et al. [1992] also used a flat plate distributor. The increase of G_s with increasing U_d is almost the same regardless of the reactor types and the annulus aeration rate. The experimental data (G_s) of Lee et al. [1992] showed the highest G_s with the higher gap height (0.14 m) and the flat type distributor.

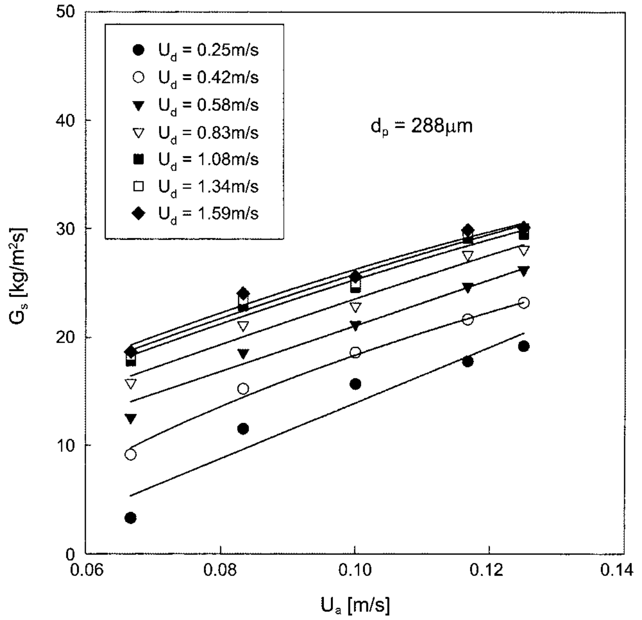

Fig. 6. Effect of U_a on G_s with variation of U_d (d_p=288 μm).

The effect of U_a (0.067-0.125 m/s) on G_s with variation of U_d (0.25-1.59 m/s) in the bed of 288 μm particles is shown in Fig. 6. As can be seen, G_s increases with increasing U_a up to the minimum fluidizing condition due to the active movement of solid particles with increasing ΔP_{or}. With increasing U_a, solid particles in the annulus section is close to the minimum fluidizing state and ΔP_{or} increases due to the increase of pressure in the annulus bed and consequent increase in G_s. Although U_a is higher than the minimum fluidizing velocity, the bed density in the annulus decreases due to bubble formation, hence G_s decrease slightly at the higher annulus gas velocities. At U_a below $0.8U_{mf}$, solid circulation does not occur; however, G_s increase markedly at $1.0U_a/U_{mf}$. Yang and Kearins [1978] reported that G_s at the lower annulus gas velocity are similar to that without annulus gas flow but G_s increase sharply at the annulus gas velocity at $0.6U_{mf}$. According to Ahn et al. [1999], G_s increase significantly with increasing U_a but are less affected by U_d.

The effect of U_a on G_s in the present and previous studies is shown in Fig. 7. As can be seen, G_s increase linearly with U_a from 0.8 to $1.5U_{mf}$ as reported previously [Lee et al., 1991; Song et al., 1997; Ahn et al., 1999]. The annulus section is operated at the bubbling fluidized bed condition with U_a>$1.6U_{mf}$ and G_s decrease due to the reduction of bed density difference. Therefore, the annulus must be operated at U_a around $1.5U_{mf}$.

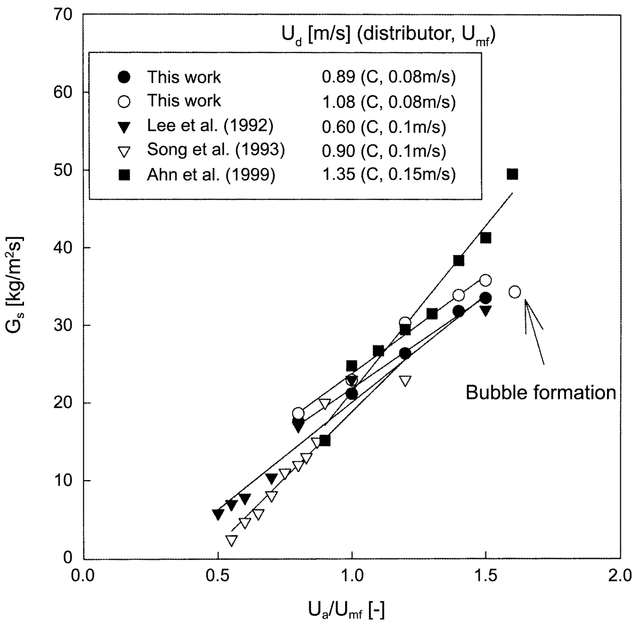

Fig. 7. Comparison of G_s at different U_d (C: conical distributor, F: flat plate distributor).

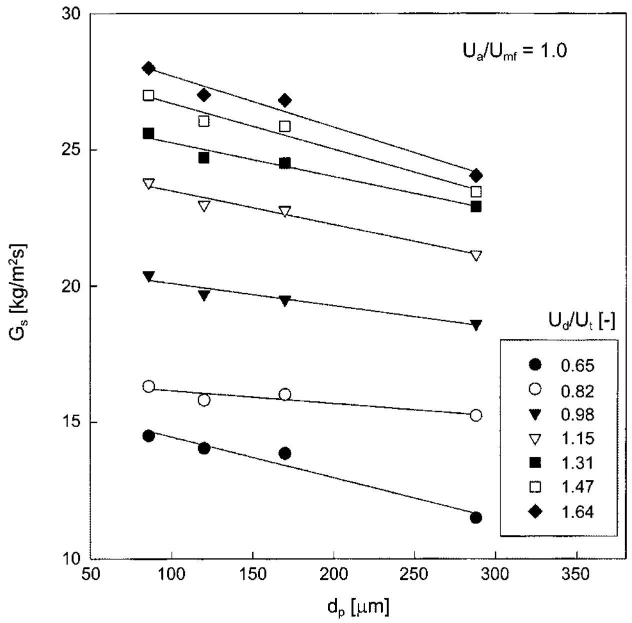

Fig. 8. Effect of particle size on G_s.

The effect of particle size (d_p) on G_s is shown in Fig. 8 where G_s decrease by 7-21% with increasing particle size from 86 to 288 μm since resistance of solid flow across the orifice increases with particle size. Ahn et al. [1999] studied solid circulation rate of sand particles (300-600 μm) as the bed material at the given gas velocities in the annulus and draft tube sections. They found that G_s decrease by 20-25% with increasing particle size due to the increase of gas bypassing from the annulus to the draft tube section. Therefore, the actual aeration gas velocity decreases due to gas bypassing so that larger particles in the annulus section (moving bed) cannot attain the minimum fluidizing condition at the calculated minimum fluidizing velocity of the given particle siz, e thereby G_s decrease with increasing particle size.

3. Correlation Between ΔP_{or} and G_s

The experimental data indicate that ΔP_{or} is closely related to solids flow through an orifice at the given gas velocity. The obtained ΔP_{or} in the present study has been correlated with the dimensionless terms as:

$$\Delta P_{or} = 715.5\left(\frac{U_d}{U_t}\right)^{0.493}\left(\frac{U_a}{U_{mf}}\right)^{0.672}\left(\frac{d_p}{d_{or}}\right)^{-0.01} \qquad (1)$$

with a correlation coefficient of 0.91.

A parity plot of ΔP_{or} between the experimental and calculated values from Eq. (1) is shown in Fig. 9.

The solid circulation rate (G_s) can be expressed by the Bernoullis equation [Judd and Dixon, 1978]:

$$G_s = C_s\left(\frac{S_{or}}{S_a}\right)\sqrt{2\rho_a \Delta P_{or}} \qquad (2)$$

where C_s, S_{or}, S_a, and r_a are particle discharge coefficient, orifice area, annulus area and annulus bed density, respectively.

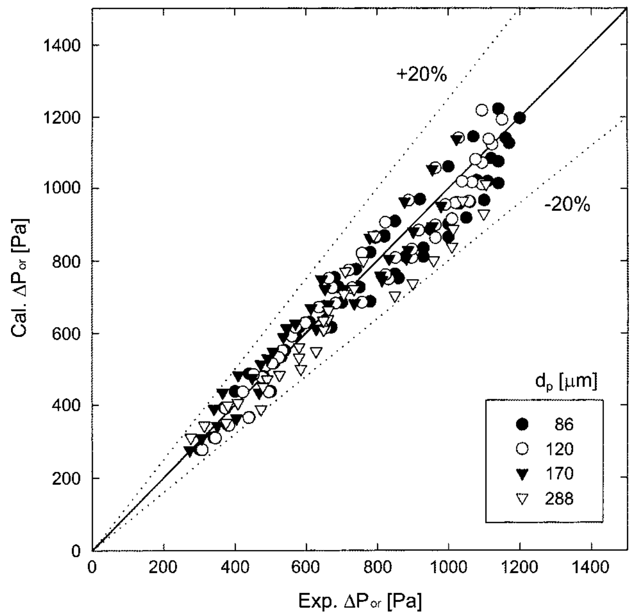

Fig. 9. Parity plot of ΔP_{or} calculated from Eq. (1) and the present experimental data.

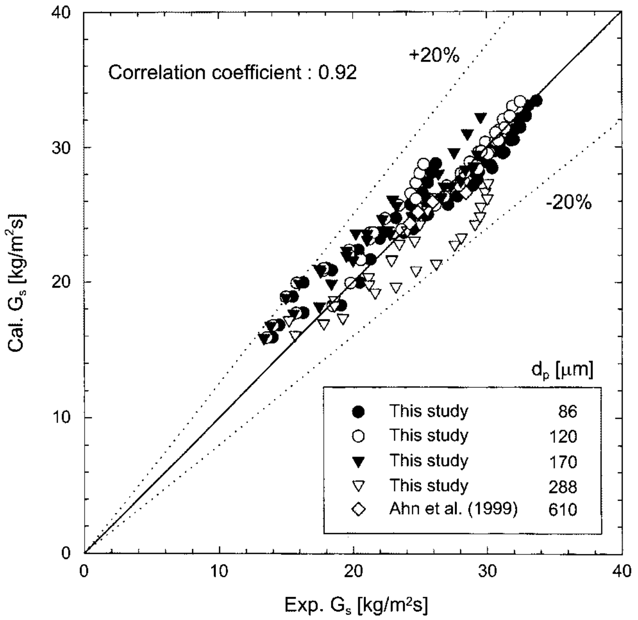

Fig. 10. Parity plot of G_s calculated from Eq. (4) and G_s data of the present and a previous study [Ahn et al., 1999] in an ICFB.

From Eq. (2), G_s can be expressed as a root square ΔP_{or}. With the assumption that the bed density in the annulus is equal to that of minimum fluidized bed condition, Eq. (2) can be expressed as:

$$G_s = C_s\left(\frac{S_{or}}{S_a}\right)\sqrt{2\rho_s(1-\varepsilon_{mf})\Delta P_{or}} \quad (3)$$

Based on the experimental data, the optimum particle discharge coefficient (C_s) in Eq. (3) is found to be 0.31 with a correlation coefficient of 0.92.

The parity plot between the experimental and predicted values of G_s from Eq. (3) is shown in Fig. 10.

CONCLUSION

Solid circulation characteristics in an internally circulating fluidized bed reactor with a draft tube have been determined. The ΔP_{or} and G_s increase with increasing U_d due to the increase of the bed density difference between the draft and annulus sections. With increasing U_a, ΔP_{or} increases up to the minimum fluidizing condition due to increase of pressure drop in the annulus section. With increasing U_a, G_s increase due to the active solid movement with higher solid flow velocity across the orifice. With increasing particle size from 86 to 288 μm, ΔP_{or} and G_s decrease by 5-23% and 7-21%, respectively, due to the resistance of solid flow through orifice. To predict G_s, a correlation is developed based on the Bernoullis equation and mass balance as

$$G_s = 0.31\left(\frac{S_{or}}{S_a}\right)\sqrt{2\rho_s(1-\varepsilon_{mf})\Delta P_{or}}$$

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NOMENCLATURE

C_s : particle discharge coefficient [-]
d_{or} : orifice diameter [m]
d_p : particle diameter [m]
G_s : mass flux in annulus [kg/m^{2}s]
ΔP_{or} : pressure drop across the orifices [kPa]
S_a : cross-sectional area of annulus [m^2]
S_{or} : cross-sectional area of orifices [m^2]
U_a : gas velocity in annulus [m/s]
U_d : gas velocity in draft tube [m/s]
U_{mf} : minimum fluidization gas velocity [m/s]
U_t : terminal velocity of a falling particle [m/s]

Greek Letters

ε_{mf} : voidage of bed at U_{mf} [-]
ρ_a : annulus bed density [kg/m^3]
ρ_s : solid density [kg/m^3]

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