

## 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.  $\times$  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 ( $\Delta P_{or}$ ). However, the values of  $G_s$  decrease by 7-21% with increasing particle size from 86 to 288  $\mu\text{m}$ . The pressure drop across the orifice increases with increasing  $U_d$  and  $U_a$ . However,  $\Delta P_{or}$  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  $\Delta P_{or}$ .

**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.  $\times$  2 m high) with a centrally located draft tube (0.1 m I.D.  $\times$  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 60° 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 45° 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  $\mu\text{m}$ ) 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.

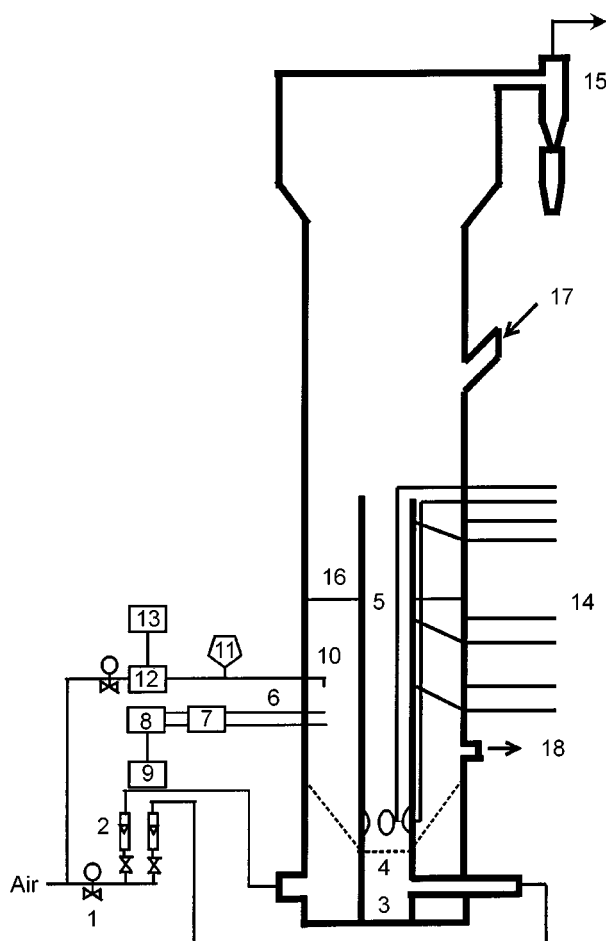


Fig. 1. Schematic diagram of experimental apparatus.

- |                            |                           |
|----------------------------|---------------------------|
| 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 acquisition 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 [ $\mu\text{m}$ ] | 86     | 120    | 170    | 288    |
| Density [ $\text{kg/m}^3$ ]             | 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   |

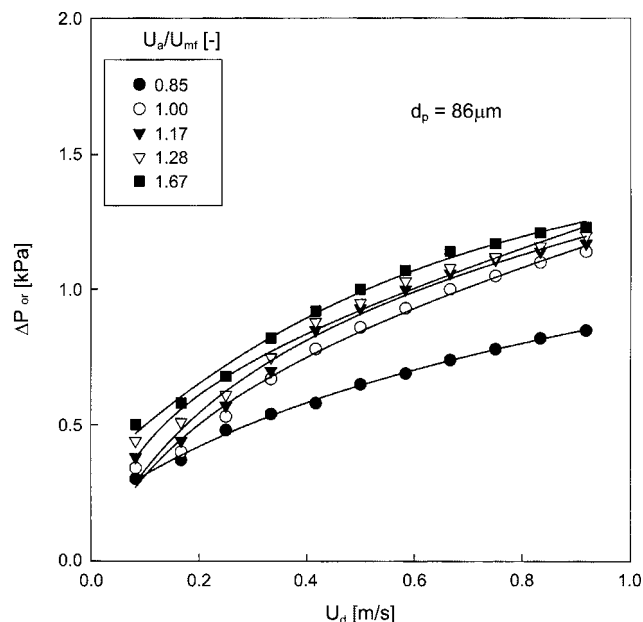


Fig. 2. Effect of  $U_d$  on  $\Delta P_{or}$  with variation of  $U_a$  ( $d_p = 86 \mu\text{m}$ ).

to 1.6 m/s), to the annulus section (moving bed, up to 0.125 m/s) and particle size (86, 120, 170, 288  $\mu\text{m}$ ) 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  $\Delta P_{or}$  with variation of  $U_a/U_{mf}$  (0.85–1.67) is shown in Fig. 2 where  $\Delta P_{or}$  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-

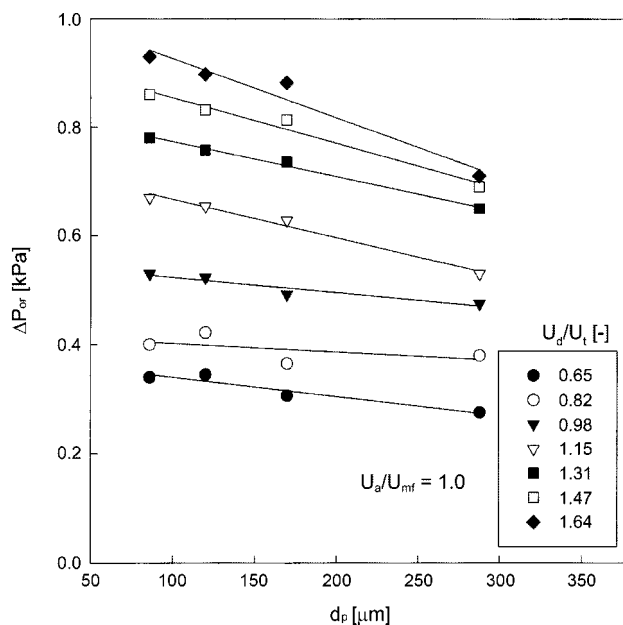


Fig. 3. Effect of particle size on  $\Delta P_{or}$ .

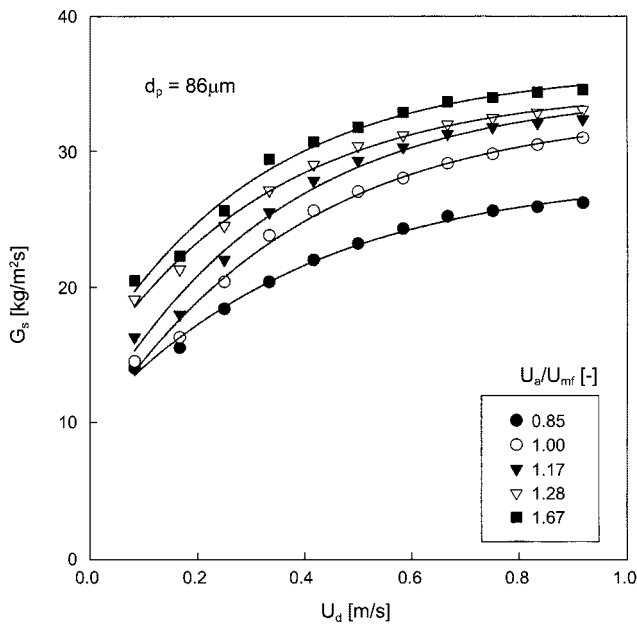


Fig. 4. Effect of  $U_d$  on  $G_s$  with variation of  $U_a$  ( $d_p=86 \mu\text{m}$ ).

dition. Therefore, both  $\Delta P_{or}$  and density difference between the draft tube and annulus section increase with increasing  $U_d$ . At  $U_d/U_{mf}$  below 0.8,  $\Delta P_{or}$  is rather small and increases sharply with increasing  $U_d/U_{mf}$  from 0.8 to 1.0. With increasing  $U_d$ ,  $\Delta P_{or}$  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  $\Delta P_{or}$  with variation of  $U_d/U_{mf}$  (0.65-1.64) at 1.0  $U_d/U_{mf}$  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,  $\Delta P_{or}$  decreases by 5-23%; whereas,  $\Delta P_{or}$  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  $U_a$  (0.85-1.67  $U_{mf}$ ) 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  $\Delta P_{or}$  (Fig. 2),  $G_s$  increase sharply at 1.0  $U_d/U_{mf}$  compared at 0.85  $U_d/U_{mf}$ . 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 2  $U_{mf}$  even if the gas velocity to the annulus section is high enough. According to Choi and Kim [1991],  $U_d$  must be higher than 2.5  $U_{mf}$  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

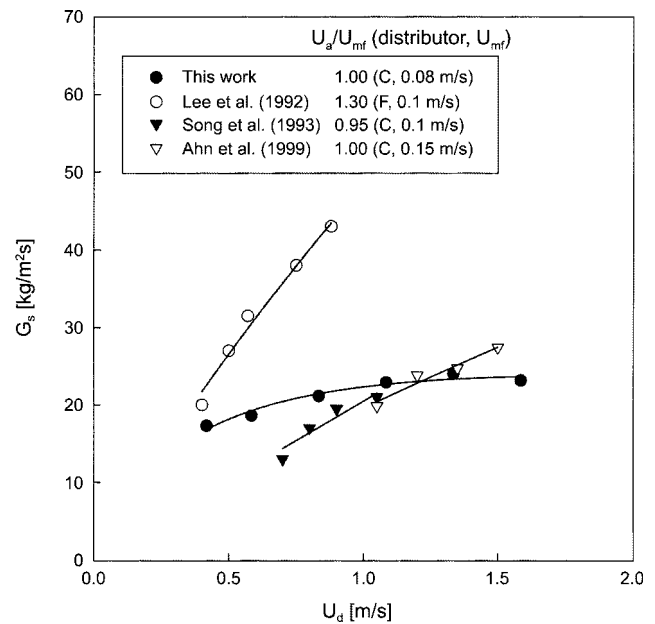


Fig. 5. Comparison of  $G_s$  at different  $U_a/U_{mf}$  (C: conical distributor, F: flat plate distributor).

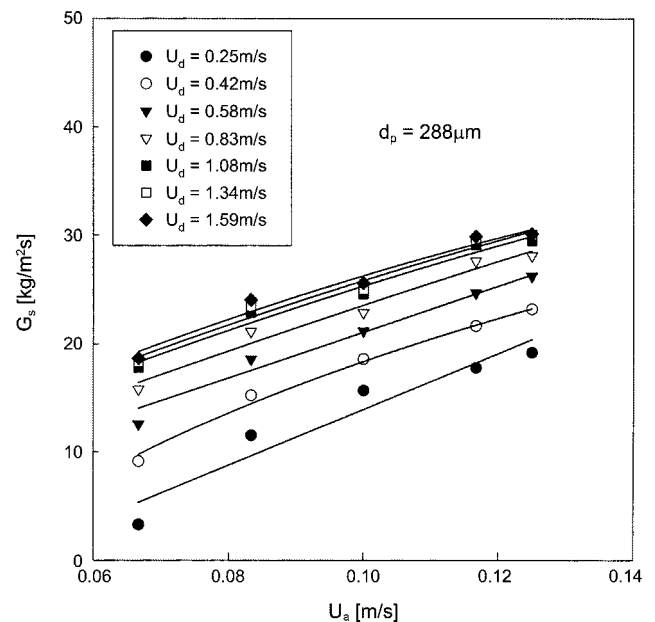


Fig. 6. Effect of  $U_a$  on  $G_s$  with variation of  $U_d$  ( $d_p=288 \mu\text{m}$ ).

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.

The effect of  $U_d$  (0.067-0.125 m/s) on  $G_s$  with variation of  $U_a$  (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  $U_d$  up to the minimum fluidizing condition due to the active movement of solid particles with increasing  $\Delta P_{or}$ . With increasing  $U_d$ , solid particles in the annulus section is close to the minimum fluidizing state and  $\Delta P_{or}$  increases due to the increase of pressure in the annulus bed and consequent increase in  $G_s$ . Although  $U_d$  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

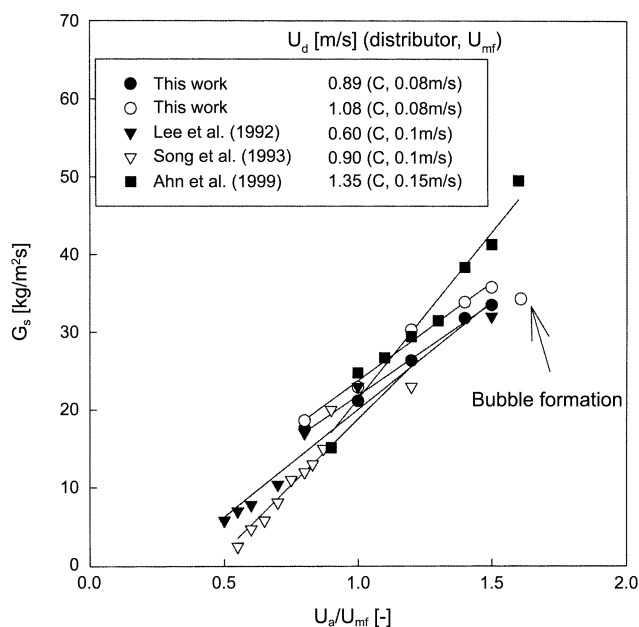


Fig. 7. Comparison of  $G_s$  at different  $U_d$  (C: conical distributor; F: flat plate distributor).

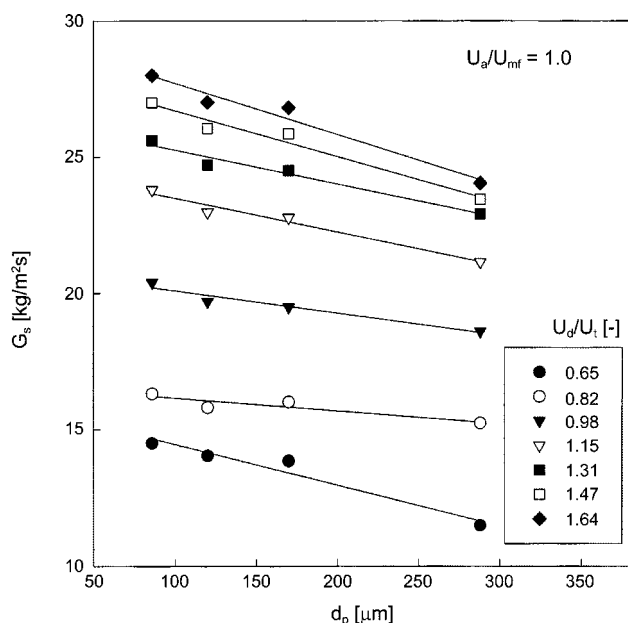


Fig. 8. Effect of particle size on  $G_s$ .

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  $1.5U_{mf}$ .

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  $\mu\text{m}$  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  $\mu\text{m}$ ) 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 size, thereby  $G_s$  decrease with increasing particle size.

### 3. Correlation Between $\Delta P_{or}$ and $G_s$

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

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

with a correlation coefficient of 0.91.

A parity plot of  $\Delta P_{or}$  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 Bernoulli equation [Judd and Dixon, 1978]:

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

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

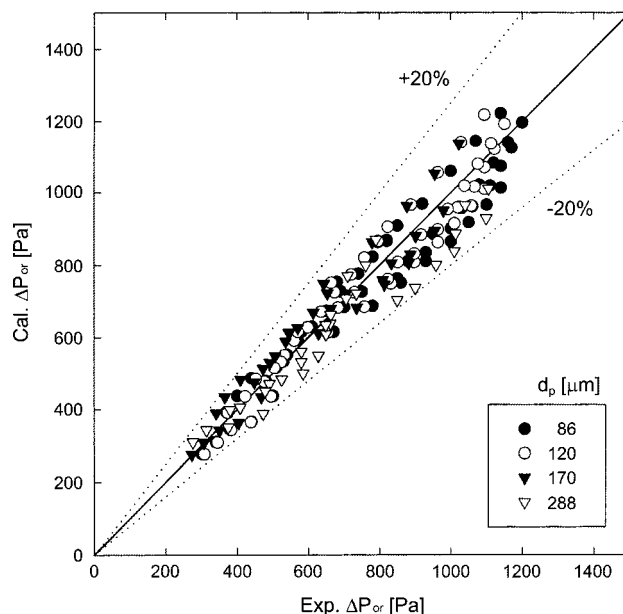


Fig. 9. Parity plot of  $\Delta P_{or}$  calculated from Eq. (1) and the present experimental data.

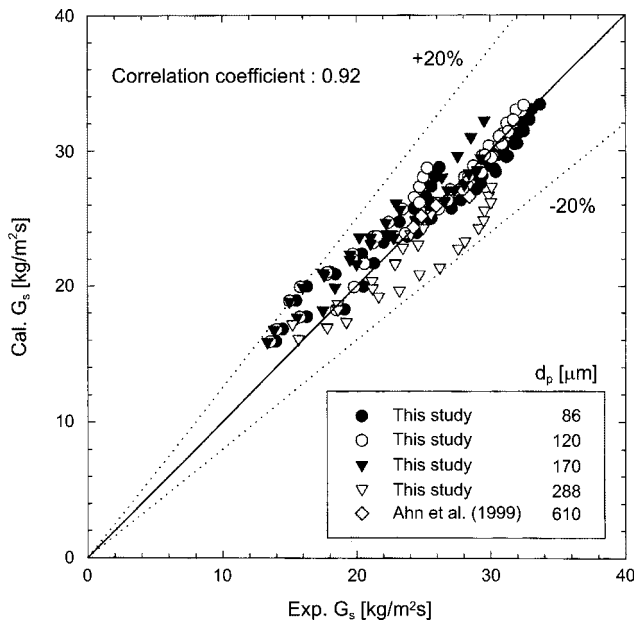


Fig. 10. Parity plot of  $G_s$  calculated from Eq. (4) and  $G_s$  data of the present and a previous study [Ahn et al., 1999] in an ICFB.

From Eq. (2),  $G_s$  can be expressed as a root square  $\Delta P_{or}$ . 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:

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

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  $\Delta P_{or}$  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  $U_a$ ,  $\Delta P_{or}$  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  $\mu\text{m}$ ,  $\Delta P_{or}$  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 Bernoulli equation and mass balance as

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

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ence and Technology, Korea.

### NOMENCLATURE

|                 |                                                     |
|-----------------|-----------------------------------------------------|
| $C_s$           | : particle discharge coefficient [-]                |
| $d_{or}$        | : orifice diameter [m]                              |
| $d_p$           | : particle diameter [m]                             |
| $G_s$           | : mass flux in annulus [ $\text{kg/m}^2\text{s}$ ]  |
| $\Delta P_{or}$ | : pressure drop across the orifices [kPa]           |
| $S_a$           | : cross-sectional area of annulus [ $\text{m}^2$ ]  |
| $S_{or}$        | : cross-sectional area of orifices [ $\text{m}^2$ ] |
| $U_a$           | : 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

|                 |                                           |
|-----------------|-------------------------------------------|
| $\epsilon_{mf}$ | : voidage of bed at $U_{mf}$ [-]          |
| $\rho_a$        | : annulus bed density [ $\text{kg/m}^3$ ] |
| $\rho_s$        | : solid density [ $\text{kg/m}^3$ ]       |

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