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Loop-seal Operation of Iron Ore Particles in Pneumatic Conveying

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Abstract−Loop-seal operation characteristics have been determined in pneumatic conveying (0.078 m ID×6.0 m high) with iron ore particles (680 μm and 4,500 kg/m^3). Solids circulation rates through the loop-seal increase linearly with increasing vertical aeration rate at constant bottom aeration. When the aeration air is injected at the weir section and the lowest point of vertical section, stable higher solids circulation rates are obtained. The solids circulation rates are predicted by using pressure drop measured in fully developed region of riser. The calculated solids circulation rates are in good agreement with the measured values.

Key words: Loop-Seal, Iron Ore Particles, Solid Circulation Rate

INTRODUCTION

Solid recycle systems transfer particles from lower to higher pressure points, provide gas sealing against the undesirable flow direction, and regulate solid circulation rate [Rudolph et al., 1991]. It is known that most shutdowns in solid processing plants are caused by the failure of the solids recycle system [Merrow, 1985]. Therefore, proper control of a solid recycle system is very important for stable operation in CFB (Circulating Fluidized Bed) or pneumatic conveying [Kim and Kim, 2002].

Solid recycle devices can be divided into mechanical and non-mechanical valves. Mechanical valves cannot be adapted under high temperature and pressure because of sealing and mechanical problems. Non-mechanical valves such as loop-seals, L-, J-, and V-valves are commonly employed in hard environments in the presence of corrosive gases, abrasive particles and high temperature and pressure [Arena et al., 1998] since they do not have moving parts. In CFB systems, loop-seals and L-valves are generally used among non-mechanical valves [Basu et al., 1999]. To date, some researchers have reported studies on L-valves [Yang and Knowlton, 1993; Geldart and Jones, 1991; Arena et al., 1998], but comprehensive design data or results on loop-seals are rare in the published literature [Basu et al., 1999]. Recently, Kim and Kim [2002] investigated the effect of particle properties on solid recycle in a loop-seal using FCC and sand, and Cheng and Basu [1999] studied the effect of pressure on loop-seal operation. Kim et al. [2000] proposed an improved loop-seal where vertical air was injected tangentially downward to the wall of the loop-seal. They obtained higher stable solid flow rates using the improved loop-seal. However, until now, studies on loop-seals using larger and denser particles such as iron ore (Geldart group D) have been scarce. The operation of non-mechanical valves is affected by particle characteristics [Arena et al., 1998] and iron ore particles (Geldart group D) have different fluidizing characteristics. Therefore, a study on loop-seal using iron ore particles is required to operate stably.

In CFB or pneumatic conveying, solid circulation rate (G_s), which is an important design parameter and the most critical variable in predicting reactor performance, is needed to predict reactor performance [Berruti et al., 1988]. The pressure drop provides very useful hydrodynamic information on the riser. In ICFB (Internally Circulating Fluidized Bed), Namkung et al. [2001] proposed a model to predict G_s from room temperature to 940 °C using the pressure drop measured in the riser. Lech [2001] predicted G_s using pressure drop due to solids in pneumatic conveying. Cheng and Basu [1999] predicted G_s using pressure drop in recycle pipe. Using pressure drop is a very useful method for obtaining G_s because it can be measured easily even at high temperature and high pressure. However, the study on prediction of G_s based on the pressure drop in pneumatic conveying is rare.

In this study, the operation characteristics of a loop-seal with iron ore particles have been determined, and the solid circulation rates are predicted by using pressure drop measured in fully developed regions of the riser in pneumatic conveying.

EXPERIMENTAL

The experimental apparatus, which is shown in Fig. 1, consists of a vertical pneumatic conveying line (riser), cyclone, hopper, downcomer and loop-seal. The riser made of stainless steel has a diameter of 0.078 m and a height of 6.0 m. The solid recycling system consists of a downcomer and a loop-seal (0.05 m ID) as a solids feeding device. The solid particles used in this study are iron ore with a mean diameter of 680 μm and an apparent density of 4,500 kg/m^3. The entrained particles from the riser were collected by the cyclone and stored in the hopper. A bag filter trapped the particles not collected in the cyclone. The solid particles from the hopper were transferred into a loop-seal through a downcomer, and were fed to the riser through the loop seal with regulation of solids circulation rate by aeration. The superficial gas velocity (U_g) and the solids circulation rate (G_s) were varied in the range of 10-23 m/s and 0-200 kg/m^{2}s, respectively. The U_g was kept at higher than 10 m/s because choking velocity

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

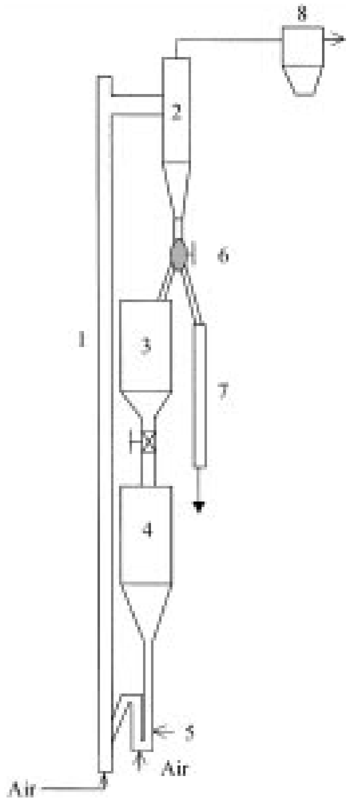

Fig. 1. Experimental apparatus.

1. Riser	6. Three-way valve
2. Cyclone	7. Sampling tube
3, 4. Hopper	8. Bag filter
5. Loop-seal	

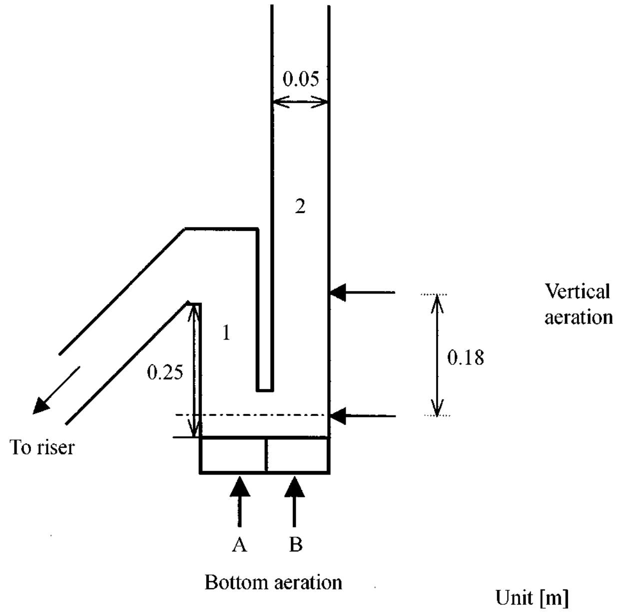

Fig. 2. Schematic diagram of loop-seal.
1. Weir section 2. Vertical section

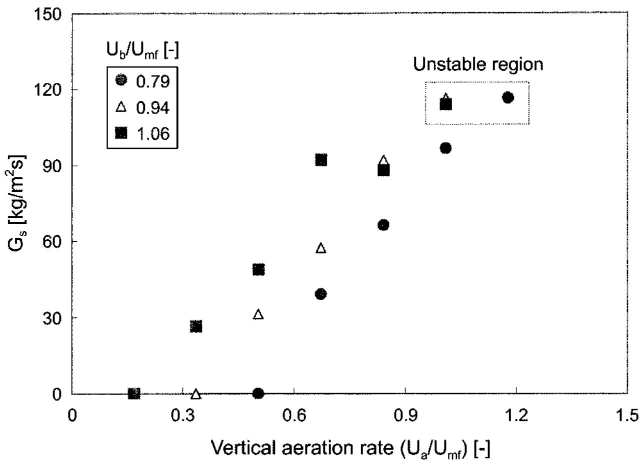

Fig. 3. Effect of vertical aeration rate on solids circulation rate.

calculated by various correlations [Knowlton and Bachovchin, 1976; Punwani et al., 1976; Yang, 1983] was in the range of 4.6-8.32 m/s depending on G_s. The gas velocity of riser was kept 11.6 m/s when the loop-seal operation characteristics were determined. The solid inventory was 50 kg under the given experimental conditions. To determine G_s at a steady state condition, the entire particle flow was changed to the measuring column by three-way valve. The descending time of particles along the known distance was measured in the transparent measuring column. With the knowledge of bulk density and the measured time, G_s can be determined. The pressure transducers were connected to pressure taps along the column height to measure pressure drops between the different locations in the riser. The pressure signals from the pressure transducer were amplified and sent via an A/D converter to a personal computer for recording.

A conventional loop-seal made of Plexiglas (0.05 m ID) is shown in Fig. 2. As shown in Fig. 2, the loop-seal consists of weir and vertical section. Air was injected into the loop-seal at two locations. A perforated distributor was located at the bottom of the loop-seal for bottom aeration and the other was located perpendicular to the wall of the vertical section in the loop-seal for vertical aeration. For the bottom aeration, a barrier was installed at the middle point of wind box to provide air independently to the weir section. For vertical aeration, air was injected at one of a variety of heights above the horizontal section of the loop-seal.

RESULTS AND DISCUSSION

1. Characteristics of Loop-seal

Effect of vertical aeration rate on G_s is shown in Fig. 3. The vertical aeration is injected at the length-to-diameter ratio of 3.6 and the bottom aeration is injected at both sides varying in the range of 0.79-1.06 U_b/U_{mf}. As can be seen in Fig. 3, when the vertical aeration is low, the solid particles do not flow to the riser. As the vertical aeration increases at the identical bottom aeration, the particles begin to flow with fluidity and G_s increases linearly with increasing vertical aeration rate. However, unstable operation is observed near 1 U_{mf}. Pressure drop fluctuation in the riser at unstable condition of loop-seal is shown in Fig. 4. The pressure drop in the riser depends on solid load in the riser. As can be seen, the pressure fluctuation is very unstable with higher frequency and amplitude when the vertical aeration rate is near 1 U_{mf}. This is because formation and extinction of large bubbles or slugs in the vertical tube of loop-seal is re-

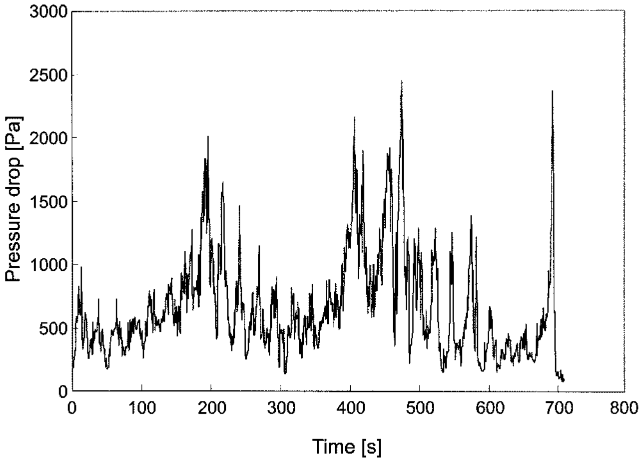

Fig. 4. Pressure drop fluctuation in riser at unstable region.

peated continuously. Thus, the solid flow rate to the riser is not constant. The stagnant void or bubble may obstruct the downflow of solids since the net opening area for particle flow would be the difference between the cross-sectional areas of the downcomer and the void [Kim et al., 2000]. Beyond 1-1.2 U_{mf}, operation is not possible because larger bubbles or voids stagnate near the aeration point. Unstable operations caused by large bubbles in the loop-seal have been observed by some researchers. Kim [1997] observed unstable operation when the vertical aeration was near the 6.0 U_{mf} with FCC particles. At higher aeration rate, Ozawa et al. [1991] found very unstable solid flow and irregular oscillation in L-valve operation with sand particles. Reddy Karri et al. [1995] reported that the limiting flow condition in the hybrid standpipe was due to large gas bubble bridging across the diameter in the vertical sections. Therefore, it is necessary to get stable higher G_s preventing formation of large bubbles or slugs in the vertical section. In this study, large bubbles are formed if gas velocity lies in the range of 1.0-1.2 U_{mf}. Therefore, the air is injected at the weir section only for bottom aeration and at the lowest point of the vertical section to minimize the air injection into vertical section to prevent the formation of larger bubbles or voids.

Effect of bottom aeration rate (U_{bw}) on solids circulation rate is shown in Fig. 5 when the bottom air is injected at the weir section only. As can be seen, G_s increases with increasing bottom aeration rate at constant vertical aeration rate. With no vertical aeration, G_s is very low because the particle movement in the loop-seal is not good. When the bottom aeration is 1.4 U_{mf}, an increase of G_s is observed with no vertical aeration. Further increase of aeration rate makes operation unstable with formation of large bubbles or voids. Although, Basu et al. [1999] reported that G_s reaches 100 kg/m^{2}s as the air is injected at the weir section (recycle chamber) with no vertical aeration, in this study, G_s is very low with no vertical aeration. As can be seen, G_s increases with increasing bottom aeration rate (U_{bw}) at constant vertical aeration of 0.84 U_a/U_{mf}. Initially, gas injected into a loop-seal flows upwards through voidage between particles in the downcomer [Kim et al., 1999]. The gas flow between particles produces frictional drag on particles in the direction of particle flow so that pressure builds up across the downcomer. If pressure drop across the downcomer is larger than the pressure drop that is needed to overcome resistance of solid flow, solid particles flow through the loop-seal [Kim et al., 2000]. As can be seen in Fig. 5, G_s increases linearly with increasing vertical aeration rate to 200 kg/m^{2}s. Above that aeration rate, G_s becomes almost constant irrespective of increasing aeration rate.

As shown in Fig. 3, stable higher G_s is not obtained when the air is injected at both sides (A and B in Fig. 2) for bottom aeration. Therefore, bottom air is injected at weir section only (A in Fig. 2). Effect of vertical aeration rate on G_s at identical bottom aeration rate (U_{bw}) is shown in Fig. 6 when the vertical aeration is injected at length-to-diameter ratio of 0.0. The bottom aeration rate (weir section only, U_{bw}) is kept 1.06 U_{mf}. G_s through the loop-seal increases linearly to a maximum value with increasing aeration rates up to 0.9 U_{mf} due to the increase of frictional drag on the particles [Kim et al., 1999]. As can be seen, with changing the aeration location at identical aeration rate, G_s increases about 1.8 times compared to when bottom air is injected at both sides and vertical air is injected at the height-diameter ratio of 3.6. And the stable operation is obtained near the 0.9-1.1 U_{mf}, although the operation is limited beyond 1.2 U_{mf} due to the formation of large bubbles or voids. It is known that the location of vertical aeration is desirable as low as possible in the nonmechanical valve to get maximum standpipe length, which

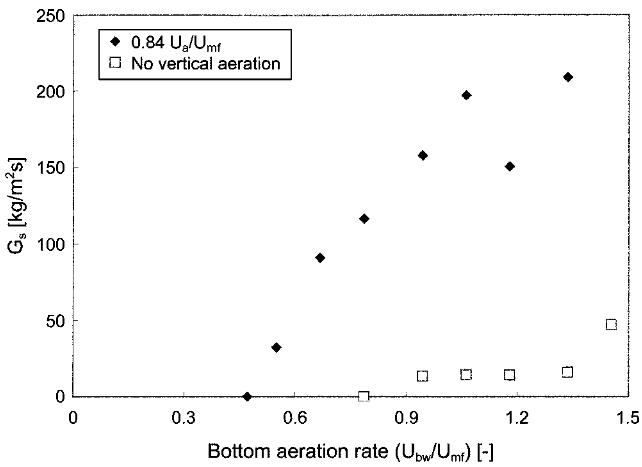

Fig. 5. Effect of bottom aeration rate (weir aeration only) on solid circulation rate with and without vertical aeration.

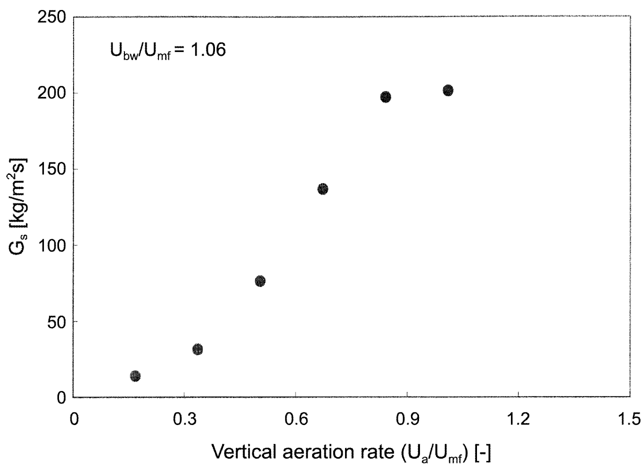

Fig. 6. Effect of vertical aeration rate on solid circulation rate at a given bottom aeration rate (weir aeration only).

results in increasing the maximum solid flowrate through the valve, while if aeration height is too low, gas bypassing results and solids flow control are insensitive and not effective [Knowlton, 1986]. Therefore, Kim et al. [1999] proposed that the optimum height of vertical aeration was a length-to-diameter ratio of 2.5. However, in the case of iron ore particles (Geldart D particle), bubbles coalesce rapidly and grow to large size [Kunii and Levenspiel, 1991]. Therefore, when the aeration gas is injected into the vertical section, large bubbles or slugs are easily formed so that the solid flow into the loop-seal is restricted. But, when the air is injected at the weir section only and the lowest point of the vertical section, the gas amount injected into the vertical section is minimized; thus the formation of large bubbles or slugs is suppressed and consequently a stable higher G_s is obtained.

Effect of vertical aeration rate on G_s of FCC, sand and iron ore particles is shown in Fig. 7. Physical properties of particles are summarized in Table 1. As can be seen, three kinds of particles exhibit similar increase in G_s with increasing vertical aeration rate. The maximum G_s increases with increasing particle size and density irrespective of experimental condition, although operation range of U_a/U_{mf} becomes narrow as particle size and density increases. Higher U_a/U_{mf} is required to attain the maximum G_s with Geldart group A particles because the injected air could not easily rise through interstices among the Group A particles due to the lower gas permeability through voidage in small particles [Knowlton, 1988]. As the particle size and density increase, local bubbles or voids are formed at relatively lower aeration rates (U_a/U_{mf}) due to different particle properties. Consequently, the mass flux of iron ore particles becomes constant at relatively lower aeration rates (U_a/U_{mf}). The G_s of Geldart group D particles is superior to Geldart group A and B particles, and G_s of Geldart group A is lower than that of Geldart group B because resistance to gas flow through Geldart A particles is about four to five times that of Geldart B particles [Reddy Karri and Knowlton, 1992].

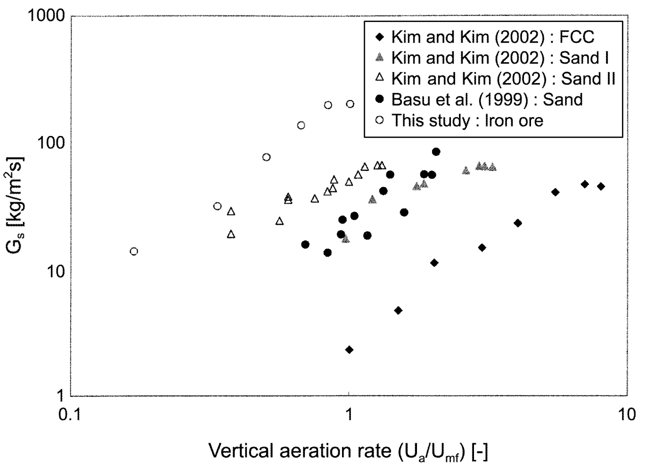

Fig. 7. Effect of vertical aeration rate on solids circulation rate of particles with different size and density.

Table 1. Physical properties of FCC, silica sand and iron ore particles

Properties	Kim and Kim [2002]			Basu et al. [1999]	This study
	FCC	Sand I	Sand II		
Mean diameter [μm]	65	101	239	350	680
Apparent density [kg/m^3]	1720	3120	3120	2382	4500
U_{mf} [m/s]	0.0027	0.0108	0.0468	0.115	0.505

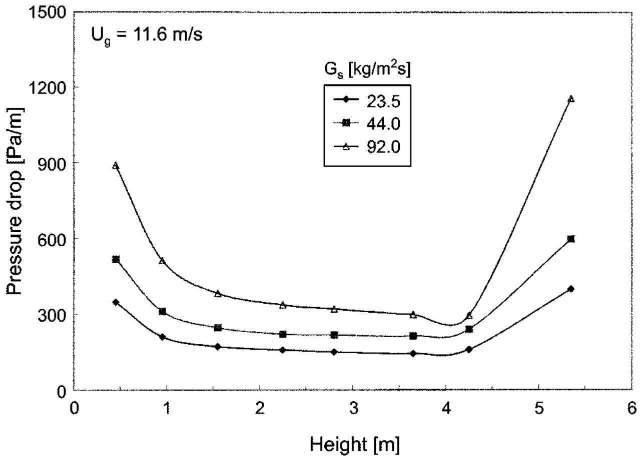

Fig. 8. Axial pressure drop profile in riser.

2. Prediction of Solids Circulation Rate

The axial pressure drop profiles in the riser are shown in Fig. 8. The pressure drop increases with increasing G_s at a constant gas velocity because the static head and friction pressure drop due to particles increase with increasing G_s [Plasynski et al., 1994]. As shown in Fig. 8, due to the particle acceleration, the pressure drop at the bottom region of the riser decreases with increasing height to a fully developed region where it has a constant value irrespective of increasing height.

Pneumatic conveying is divided into two regions depending on operating condition: one is dense phase conveying or core-annulus flow region where downflow of particles is observed at the wall region, and the other is dilute phase conveying or uniform flow [Nakamura and Capes, 1973; Namkung et al., 2000]. Bi and Fan [1991] proposed a correlation to predict the boundary velocity between two regions as:

$$U_{PT}=10.1(gd_p)^{0.347}\left(\frac{G_s}{\rho_g}\right)^{0.310}\left(\frac{d_p}{D}\right)^{-0.139}Ar^{-0.021} \quad (1)$$

In this study, the transition velocity calculated by Eq. (1) is in the range of 6.7-13.6 m/s depending on the solid circulation rate. That is, most experiments were performed in the dilute phase pneumatic conveying region where the downflow of particles did not exist.

In the fully developed region, the pressure drop is written as

$$-\frac{dP}{dz}=[\rho_s(1-\varepsilon)+\rho_g\varepsilon]g+\frac{2f_g\rho_gU_g^2}{D}+\frac{2f_s\rho_s(1-\varepsilon)U_p^2}{D} \quad (2)$$

The solids circulation rate (G_s) is as

$$G_s=\rho_sU_p\varepsilon_s \quad (3)$$

It is important to predict the particle velocity for estimating the pressure drop and for performing mathematical modeling [Lodes and Mierka, 1989]. There are numerous correlations available in the literature for predicting particle velocity in the fully developed region of vertical pneumatic conveying as reviewed by Plasynski et al. [1994]. In the range of experimental conditions, gas holdup calculated by using various particle velocity correlations is at least above 0.99, and gas-solid flow lies in the dilute phase conveying region. Therefore, it can be assumed that there are relatively few interactions of the particles. Then, particle velocity in the fully developed region can be expressed as the slip velocity, which is the relative velocity between gas velocity and terminal velocity of particles [Plasynski et al., 1994; Konno and Saito, 1969; Leung and Wiles, 1976].

$$U_{p\infty}=U_g-U_t \tag{4}$$

Substituting Eqs. (2) and (4) into Eq. (3) yields the following equation:

$$G_s=\rho_s(U_g-U_t)\left[\frac{\frac{\Delta P}{L}-\frac{2f_g\rho_g U_g^2}{D}}{\rho_s g-\rho_s g+\frac{2f_s\rho_s(U_g-U_t)^2}{D}}\right] \tag{5}$$

Therefore, if f_g and f_s are known for a given gas-solid flow, G_s can be calculated by using Eq. (5) from measured pressure drop in fully developed region ($\Delta P/L$). In this study, f_g and f_s are calculated by using the correlation proposed by Koo [1966] and van Swaaij et al. [1970], respectively.

The comparison between experimental and calculated values of G_s is shown in Fig. 9. As can be seen, the calculated values of G_s using the model compare well with experimental ones. Therefore, one can expect G_s using pressure drop measured in fully developed region of the riser in pneumatic conveying.

CONCLUSIONS

Solids circulation rates through the loop-seal increase linearly with increasing vertical aeration rate at identical bottom aeration. When the aeration air is injected at the weir section only and the lowest point of vertical section, stable higher solids circulation rates are obtained compared to when bottom air is injected at both sides and vertical air is injected at the height-diameter ratio of 3.6. As the particle size and density increases, the maximum solids circulation rate increases. The solids circulation rates are predicted by using pressure drop measured in fully developed region of riser. The calculated solids circulation rates compare well with the measured values.

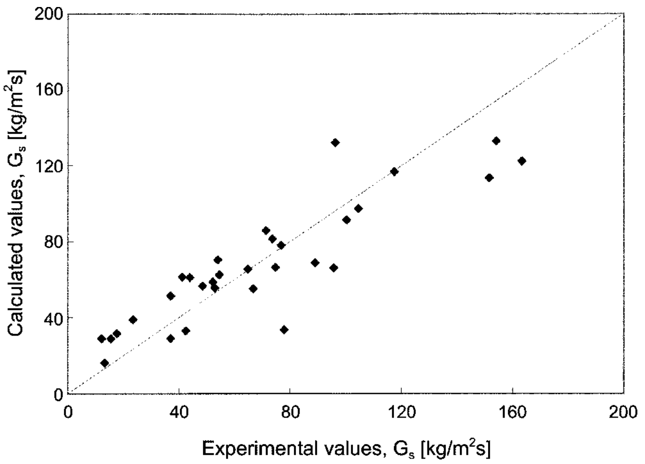

Fig. 9. Comparison between measured and calculated values of solids circulation rate.

NOMENCLATURE

- D : riser diameter [m]
- f_g : gas friction factor [-]
- f_s : particle friction factor [-]
- g : acceleration of gravity [m/s^2]
- G_s : solids circulation rate [kg/m^{2}s]
- U_a : vertical aeration rate [m/s]
- U_b : bottom aeration rate [m/s]
- U_{bw} : bottom aeration rate through weir section only [m/s]
- U_g : superficial gas velocity [m/s]
- U_p : particle velocity [m/s]
- U_t : terminal velocity [m/s]
- U_{PT} : transition velocity between dilute phase pneumatic conveying and dense phase pneumatic conveying [m/s]

Greek Letters

- $\Delta P/L$: pressure drop [pa/m]
- ε : voidage [-]
- ρ_s : particle density [kg/m^3]
- ρ_g : gas density [kg/m^3]

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