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Hydrodynamic behavior of an internally circulating fluidized bed with tubular gas distributors

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Abstract To better understand the hydrodynamic behavior of an internally circulating fluidized bed, solids holdup in the down-comer (εsD), solids circulation rate (Gs) and gas bypassing fraction (from down-comer to riser γDR, and from riser to down-comer γRD) were experimentally studied. The effects of gas velocities in the riser and in the down-comer (UR and UD), orifice diameter in the draft tube (dor), and draft tube height (HR) were investigated. Experimental results showed that increase of gas velocities led to increase in Gs, and slight decrease in γRD. Larger orifice diameter on the draft tube led to higher εsD, Gs and γDR, but had insignificant influence on γRD. With increasing draft tube height, both Gs and γDR first increased and then decreased, while γRD first decreased and then increased. Proposed correlations for predicting the hydrodynamic parameters agreed reasonably well with experimental values.

Keywords Internally circulating fluidized bed; Solids holdup; Solids circulation rate; Gas bypassing fraction

1. Introduction

High-purity polycrystalline silicon is the main raw material for monocrystalline silicon for solar cell. With the rapid development of photovoltaic industry, the demand for polycrystalline silicon has increased dramatically in the last decade (Surek, 2005). The traditional method for producing
high purity polysilicon is the Siemens process that uses the decomposition of trichlorosilane (TCS) on a high purity silicon rod in a bell-jar reactor. The Siemens process is a mature technology for producing high quality products, but has the disadvantages of high energy consumption and low production efficiency. As a result, new technologies for polysilicon using the fluidized bed reactor have been extensively studied. However, the fluidized bed reactor suffers from wall deposition, especially when external heating is used. To overcome this problem, the internally circulating fluidized bed (ICFB) could be used to provide separate heating and reaction zones. The ICFB, somewhat similar to the spouted bed, has a draft tube as riser and an annular zone as down-comer, as reported by San José, Olazar, Peñas, Arandes and Bilbao (1995). Gas is pumped to these two zones separately, producing different fluidization states in different gas atmospheres. Wall deposition in the reactor could be solved by reducing gas bypassing from the riser to the down-comer (Kinoshita, Kojima, & Furusawa, 1987). In addition, the effective contact area between gas and solids in ICFB could be 2 to 3 orders of magnitude higher than that in the Siemens process. Hydrodynamic behaviors evidently play an important role in producing polycrystalline silicon.

Solids holdup in the down-comer ($\varepsilon_s$), solids circulation rate ($G_s$) and gas bypassing coefficient ($\gamma_{DR}$ and $\gamma_{RD}$) are needed for the design of an ICFB reactor (Marschall & Mleczko 1999; Bin, Zhang, Dou, Song, & Wu, 2003; Zhang, Brandani, & Bi, 2005; Wei, Sheng, & Tian, 2006). Milne, Berruti, Behie, and Debruijn (1992) found that the solids circulation rate increased nearly linearly with increasing superficial gas velocity in the annulus, while the effect of superficial gas velocity in the draft tube was slight. Song, Kim, and Kim (1997) studied the influence of gas distributor type on solids circulation rate and gas bypassing in an ICFB with a draft tube installed at a distance from the distributor plate, finding that a conical plate distributor provided the highest solids circulation rate.

For the design of the ICFB reactor, mathematical modeling is important to predict the hydrodynamic parameters. Ahn, Lee, Kim, and Song (1999) used the equation derived by de Jong and Hoelen (1975) to fit the experimental data of solids circulation rate per orifice and determined the values of the discharge coefficient. Chu and Hwang (2002) developed a mathematical model to predict the solids circulation rate based on pressure balance around an opening in an ICFB with
gas chambers at the bottom. Shih, Chu, and Hwang (2003) studied the effects of gas velocities, average diameter of particles and geometry of the draft tube on solids circulation rate and gas bypassing, and proposed a correlation for solids circulation rate.

The temperature for producing polycrystalline silicon granules is around 1100°C, for which the reactor must be made of materials such as quartz, and the plate distributor must be fixed with a flange. The high temperature and the very small particles may easily cause sealing and plugging. Thus, a tubular distributor introduced into the ICFB from the top appears to be a better choice than the plate-type distributor generally used on ICFB. The present work aimed to experimentally study the hydrodynamic behaviors of the ICFB with a tubular gas distributor, and to determine the related parameters in mathematical modeling.

2. Experimental

2.1. Apparatus

Experiments were carried out in a transparent cold-model ICFB reactor, as shown in Fig. 1. A central riser was aerated with air from 24 orifices on a circular gas distributor at the bottom. Surrounding the central riser, the annular space was occupied by the down-comer which was aerated by air from 12 orifices on another circular gas distributor at the bottom. Silica beads \((d_p = 300 \, \mu m, \rho_p = 2.71 \, kg/m^3, U_{mf} = 0.051 \, m/s)\), used as the solid particles, flowed from the down-comer via a cylindrical draft tube with eight 16-mm holes into the riser. The above assembly of a riser and a down-comer was surmounted by an expanded section at the top to reduce particle entrainment. The experimental conditions used in this work were as follows:

- gas velocity in riser \(U_R/U_{mf}\) (4.25, 5.66, 7.08, 8.50 and 9.91)
- gas velocity in down-comer \(U_{D}/U_{mf}\) (1.10, 1.46, 1.83, 2.19 and 2.56)
- orifice diameter \(d_{or}\) (8, 10, 12, 14 and 16 mm)
- draft tube height \(H_R\) (235, 250, 265, 280 and 295 mm).

Table 1 & Fig. 1

2.2. Measuring method
2.2.1. Solids holdup in down-comer

Solids holdup in the down-comer was determined by the pressure drop method, using two pressure transducers fixed on the reactor wall. A differential pressure transducer was used to measure the axial pressure drop ($\Delta P$) through the fluidized bed. When the flowing resistance is negligible compared to the static pressure, the relationship between the solids holdup and $\Delta P$ is:

$$
\Delta P = \left[ \rho_p \varepsilon_{s,d} + \rho_f (1-\varepsilon_{s,d}) \right] gH,
$$

where $\rho_p$ and $\rho_f$ are the densities of solids and air, respectively, and $H$ is the distance between the two pressure taps. Considering that $\rho_f$ is negligible as compared to $\rho_p$, the solids holdup can be determined from the measured pressure drop as:

$$
\varepsilon_{s,d} = \frac{\Delta P}{\rho_p gH}.
$$

The orifice pressure drop ($\Delta P_{or}$), which was used to predict the solids circulation rate across the orifices, was also measured with the differential pressure transducer. The two measuring ports were connected to the riser and down-comer, respectively.

2.2.2. Particle velocity $u_p$ and solids circulation rate $G_s$

The average particle velocity was determined by a thermal tracer method. A feeding tube was fixed on the wall 50 mm below the top of the draft tube with an angle of 30° downward. When the particles in the bed were fluidized, some particles in the down-comer moved into the feeding tube and were heated by the heating wires to about 250°C. The heated particles were injected into the down-comer section with compressed air through a solenoid valve, and then the change in temperature of the fluidized bed was measured by two infrared temperature probes (Raytek compact MI, 150 ms for 95% response) located 6 cm and 14 cm below the top of the draft tube. The response signals were sampled with an A/D converter at a sampling frequency of 25 HZ and stored in a PC. The optical fibre probe was used by Olazar, San Jose, Alvarez, Morales, and Bilbao (1998) to measure instantaneous particle velocity. Vast amount of data and complex data
processing are needed to get the average solids circulation velocity. Infrared temperature probe was used in the present work to measure directly the average circulation velocity. This method has faster response as compared to the thermistor probe used by Jeon, Kim, Kim, and Kang (2008). Typical signals of the temperature changes with time are shown in Fig. 2. The particle velocity in the down-comer was determined by

\[ u_p = \frac{h}{\Delta t}, \]  

where \( h \) is the distance between the two thermocouple probes, and \( \Delta t \) is the time lag between the two response curves, which can be calculated by the cross-correlation method. The cross-correlation function of \( V_1(t) \) and \( V_2(t) \) is

\[ c(\tau) = \int_{0}^{\infty} V_1(t)V_2(t-\tau)dt, \]  

where \( V_1(t) \) and \( V_2(t) \) are the upstream and downstream signals, respectively. The time lag \( \Delta t \) has the value of \( \tau \) when \( c(\tau) \) reaches its maximum.

Fig. 2

The solids circulation rate was calculated from the average particle velocity and solids holdup in the down-comer by

\[ G_s = \rho_p\varepsilon_s u_p, \]  

2.2.3. Gas bypassing fraction

Gas bypassing fractions were measured by a tracing method together with a gas chromatograph, similar to what was used by Song, Kim, and Kim (1997). Nitrogen and carbon dioxide were used as the gases pumped into the riser and down-comer, respectively. Gas samples were taken at the bottom and middle of both the riser and the down-comer, and analyzed by a gas chromatograph (GC789, TDX-01), as shown typically in Fig. 3. Calibrations were made with a \( \text{N}_2/\text{CO}_2 \) mixture of
known fractions. The gas bypassing fraction from the riser to down-comer $\gamma_{RD}$ and that from the down-comer to riser $\gamma_{DR}$ were define as

$$\gamma_{RD} = (Q_{RD} / Q_{R1}) \times 100\%,$$

$$\gamma_{DR} = (Q_{DR} / Q_{D1}) \times 100\%,$$

where $Q_{RD}$ and $Q_{RD}$ were the gas bypassing flow rate from the riser to the down-comer and that from down-comer to riser, respectively; $Q_{R1}$ and $Q_{D1}$ were the inlet flow rates in the riser and down-comer, respectively. With the assumption that the bypassing gas has the same concentration as that of the corresponding inlet gas, i.e. $x_{R1}=x_{RD}=1$ and $x_{D1}=x_{DR}=0$, the unknown flow rates $Q_{R2}$, $Q_{D2}$, $Q_{RD}$ and $Q_{DR}$ can be calculated from mass balances, as shown in Fig. 4.

Figs. 3 & 4

The outlet flow rates $Q_{R2}$ and $Q_{D2}$ in the riser and down-comer can be calculated as:

$$Q_{R2} = \frac{x_{D2} (Q_{R1} + Q_{D1}) - Q_{R1}}{x_{D2} - x_{R2}},$$

$$Q_{D2} = \frac{Q_{R1} - x_{R2} (Q_{R1} + Q_{D1})}{x_{D2} - x_{R2}}.$$

The bypassing flow rates $Q_{RD}$ and $Q_{DR}$ can be calculated from mass balances and $N_2$ mass balances of the riser:

$$Q_{RD} = Q_{R1} - x_{R2} Q_{R2},$$

$$Q_{DR} = (1-x_{R2}) Q_{R2}.$$
3. Results and discussion

3.1. Solids holdup in the down-comer

The difference of the solids holdups in the riser and in the down-comer provides the driving force for solids circulation. Therefore, solids holdup is an important parameter for calculating the solids calculation rate \( G_s \). The effects of the superficial gas velocities \( U_R \) and \( U_D \), orifice diameter \( d_{or} \), and draft tube height \( H_R \) on solids holdup in the down-comer \( \varepsilon_{AD} \) were investigated.

3.1.1. Effect of superficial gas velocity

The effects of superficial gas velocity in the riser \( U_R \) on solids holdup in the down-comer \( \varepsilon_{AD} \) are shown in Fig. 5. With increasing \( U_R \), the solids holdup \( \varepsilon_{AD} \) decreased due to gas bypassing from the riser to down-comer through the orifices in the draft tube. Note that the decreasing rate of \( \varepsilon_{AD} \) was higher at a lower \( U_D \): \( \varepsilon_{AD} \) decreased from 0.441 to 0.408 at \( U_D/U_{mf} \) of 1.10, but decreased from 0.434 to 0.415 at \( U_D/U_{mf} \) of 4.02. The reason was that the pressure drop in the down-comer became higher with increasing \( U_D \), which led to a decrease in the pressure difference between the riser and down-comer. As a result, the decrease of \( \varepsilon_{AD} \) caused by gas bypassing from the riser to down-comer became less significant.

Fig. 5

The effect of superficial gas velocity in the down-comer \( U_D \) on \( \varepsilon_{AD} \) is shown in Fig. 6: \( \varepsilon_{AD} \) increased as \( U_D \) increased from 1.10 to 2.56, and then slightly decreased with further increase in \( U_D \). The reason was that more gas in the down-comer tended to bypass from the down-comer to riser due to increasing pressure drop in the down-comer when \( U_D \) increased, especially in the low \( U_D \) range. Fluidization quality became better as \( U_D \) decreased slightly. On one hand, gas in the downer can provide better fluidization condition and enhance solids circulation. On the other hand, gas bypassing from the riser to down-comer will be depressed with increasing \( U_D \).

Fig. 6
3.1.2. Effect of orifice diameter

The effect of orifice diameter in the draft tube \(d_{or}\) on the solids holdup in the down-comer \(\varepsilon_D\) in Fig. 7 showed that \(\varepsilon_D\) increased with increasing \(d_{or}\). The increasing rate of \(\varepsilon_D\) was independent of \(U_R\). For example, \(\varepsilon_D\) increased from 0.437 to 0.498 at \(U_R/U_{mf}\) of 4.25, and increased from 0.396 to 0.457 at \(U_R/U_{mf}\) of 9.91. Gas bypassing from the down-comer to riser increased due to decreasing flowing resistance through the orifices, which in turn led to a decreasing linear gas velocity and solids holdup in the down-comer. Note that \(\varepsilon_D\) followed the very similar trend with \(d_{or}\) at different gas velocities.

Fig. 7

3.1.3. Effect of the draft tube height

The effect of draft tube height \(H_R\) on solids holdup \(\varepsilon_D\) is shown in Fig. 8, indicating that \(\varepsilon_D\) decreased significantly with increasing \(H_R\). However, the decreasing rate of \(\varepsilon_D\) was larger from 0.493 to 0.399 at \(U_R/U_{mf}\) of 4.25, but deceased from 0.402 to 0.369 at \(U_R/U_{mf}\) of 9.91.

Fig. 8

3.2. Solids circulation rate

The solids circulation rate \(G_s\) was greatly affected by the reactor structure and operating conditions. It had a significant effect on the reactor performance, such as the solid residence time, gas-solid contact behavior, and heat and mass transfer. In the ICFB, particles flow upwards in the riser and flow downwards in the down-comer. The only way for solids incorporation into the riser is via the orifices on the bottom part of the draft tube. This is different from the solids circulation in a spouted bed without a draft tube (Olazar, San Jose, Izquierdo, de Salazar, & Bilbao, 2001). In the following section, the effects of the superficial gas velocities \(U_R\) and \(U_D\), orifice diameter \(d_{or}\), and draft tube height \(H_R\) on \(G_s\) were investigated.
3.2.1. Effect of superficial gas velocity

The effect of superficial gas velocity $U_R$ and $U_D$ on solids circulation rate $G_s$ is shown in Fig. 9. When $U_b/U_{mf}$ increased from 4.25 to 9.97, $G_s$ increased from 7.81 to 21.87 kg/m$^3$s. With an increase in $U_R$, the solids holdup in the down-comer decreased, as shown in Fig. 5, which led to an increase in the driving force for solids circulation. According to Song et al. (1997), the increasing rate of $G_s$ was smaller at higher $U_R$, due to increasing solids back-mixing in the riser. In this work, it was found that the effect of $U_R$ on $G_s$ also depended on $U_D$. At higher $U_D$, $G_s$ increased almost linearly with $U_R$; while at lower $U_D$, $G_s$ increased with $U_R$ in the low $U_R$ range and became unchanged in the high $U_R$ range. The results also showed that high $U_D$ enhanced solids circulation. The reason is that $G_s$ is affected not only by the difference between the solids holdups in the riser and the down-comer, but also by fluidization quality in the down-comer. According to experimental observation, fluidization quality in the down-comer was improved when $U_D$ increased from 1.1 to 2.56. As a result, particle circulation rate $G_s$ increased with increase in $U_D$.

Fig. 9

3.2.2. Effect of orifice diameter

With a specific number of orifices, the orifice diameter $d_o$ has a notable effect on solids circulation rate $G_s$, as shown in Fig. 10. When $d_o$ increased from 8 to 16 mm, $G_s$ increased by a factor of 3.3 to 4.0 due to decreasing flowing resistance for particle circulation though the orifices. These results were similar to those reported by Milne et al. (1992) and Ahn et al. (1999).

Fig. 10

3.2.3. Effect of draft tube height

Fig. 11 shows the effect of draft tube height $H_R$ on solids circulation rate $G_s$, reaching a maximum when $H_R$ increased from 235 mm to 290 mm. According to Shih et al. (2003), the flowing resistance in the riser increased with $H_R$, which resulted in a decrease in $G_s$ with $H_R$. Some of the particles which circulated from the riser to the down-comer flowed back to the riser.
when the bed surface in the riser was lower than \( H_R \). This phenomenon did not occur in this work because the bed surface was always higher than \( H_R \). Friction between the particles and riser wall was insignificant because the riser used in this study was much lower than that used by Shih et al. (2003). The static bed height was 245 mm. Therefore the circulating particles over the top of the riser had two directions when \( H_R \) was lower than 245 mm. One direction was from the riser to down-comer. The other was the opposite. The height of the expanded bed in the riser was higher than that in the down-comer because the superficial gas velocity was higher in the riser. As a result, the amount of particles that flowed back from the down-comer to riser decreased with increasing \( H_R \). As a result \( G_s \) increased slightly when \( H_R \) increased from 230 to 255 mm. When \( H_R \) was higher than 255 mm, the amount of overflow particles from riser to down-comer decreased rapidly due to limited pressure head, which in turn led to a significant decrease in \( G_s \).

Fig. 11

3.2.4. Correlation of \( G_s \)

Earlier work by Kim, Kim, Roh, and Lee (2002) indicated that the pressure drop (\( \Delta P_{or} \)) across orifices was closely related to the solids flowing through the orifices at a given gas velocity. The dimensionless equation proposed by Jeon et al. (2008) was used to correlate the experimental data with the coefficients determined from the experimental data in this work. The resulted correlation for \( \Delta P_{or} \) is

\[
\Delta P_{or} = 2.389 \times 10^3 \left( \frac{U_R}{U_{mf}} \right)^{0.885} \left( \frac{U_D}{U_{mf}} \right)^{0.801} \left( \frac{d_p}{d_{or}} \right)^{0.971},
\]

with \( 3.53 \leq \frac{U_R}{U_{mf}} \leq 9.87, \ 1.10 \leq \frac{U_D}{U_{mf}} \leq 3.89, \ 1.89 \times 10^{-2} \leq \frac{d_p}{d_{or}} \leq 3.79 \times 10^{-2} \). \( G_s \) was determined by the Bernoullis equation as (Judd & Dixon, 1978)

\[
G_s = C_d \left( \frac{S_{or}}{S_D} \right) \sqrt{2 \varepsilon_{str} \Delta P_{or}},
\]

with
where $C_d$, $S_{or}$, $S_D$ are respectively the particle discharge coefficient, orifice area and down-comer area. $C_d$ was found to be 1.59 with a correlation coefficient of 0.961. The parity plots of $\Delta P_{or}$ and $G_s$ between the experimental and calculated values are shown in Fig. 12. The maximum deviation between experimental and calculated values of $\Delta P_{or}$ and $G_s$ are $\pm 25\%$ and $\pm 21\%$, with most data within $\pm 12\%$ error range. A reasonable agreement was obtained, showing that Eqs. (12) and (13) can be used to predict solids circulation rate.

Fig. 12

3.3. Gas bypassing

The gas bypassing between the riser and down-comer is an important parameter that affects reactor performance. When used for the production of granular silicon, the riser is used as the reaction zone, and the down-comer is used as the heating zone. The reaction zone is fed with trichlorosilane and hydrogen as reactants with a higher gas velocity, and the heating zone is fed with hydrogen as carrying gas with a lower gas velocity. The circulating particles provide heat transfer from the down-comer to the riser. At the same time, there is gas bypassing from the riser to the down-comer $\gamma_{RD}$ and from the down-comer to the riser $\gamma_{DR}$. A high $\gamma_{RD}$ causes significant bypassing of reactant into the heating zone, to cause unwanted wall deposition. Therefore, quantitative results on gas bypassing are needed for reactor design and optimization.

3.3.1. Effect of superficial gas velocity

The effect of superficial gas velocity was reported in our previous work (Zhao, Sha, Wang, & Wang, 2001). The results are included here to compare with those in the literature to get a better understanding of the gas bypassing behavior. When the fluidization number $U_R/U_{mf}$ increased from 4.2 to 9.9, the gas bypassing fraction $\gamma_{DR}$ increased from 48% to 77%, and $\gamma_{RD}$ decreased from 5% to 3%. The experimental results of Song et al. (1997) showed that $\gamma_{DR}$ increased from 5% to 50% and $\gamma_{RD}$ decreased from 10% to 7% with increasing $U_R$. Shih et al. (2003) reported that $\gamma_{DR}$ increased from 30% to 40% and $\gamma_{RD}$ decreased from 10% to 7% with increasing $U_R$. They found that the pressure drop across the orifices increased with increasing $U_R$, for the reason that when $U_R$ increases, the decreasing rate of solids holdup in the riser is larger than that in the down-comer.
Thus, the driving force for particles and gas flowing from the down-comer to riser is enhanced. As a result, $\gamma_{DR}$ increases and $\gamma_{RD}$ decreases with increasing $U_R$.

When $U_D$ increased, $\gamma_{DR}$ increased from 44% to 71% and $\gamma_{RD}$ decreased from 5% to 3%. Part of the gas fed into the down-comer/riser passed through the particle bed directly as fluidizing gas, and the rest flowed into the riser/down-comer through the orifice due to bypassing. The gas bypassing was closely related to the particle circulation through the orifices. A higher particle circulation rate $G_s$ resulted in a higher $\gamma_{DR}$ and a lower $\gamma_{RD}$. In the reactor of this study, the value of $\gamma_{RD}$ was below than 5.5%, which can fulfill the requirement for reactor design with two separate sections. With low gas bypassing from the riser to down-comer, the particles can be heated in the down-comer without notable deposition of reactant on the wall. Although the reactant concentration is much high in the riser, the deposition of reactant on the riser wall is also reduced because its temperature is lower than that of the down-comer wall.

### 3.3.2. Effect of orifice diameter

The effects of orifice diameter $d_{or}$ on $\gamma_{RD}$ and $\gamma_{DR}$ are shown in Fig. 13. For comparison, the previous results with a plate distributor (Zhao et al., 2011) are also included. When $d_{or}$ increased from 8 to 16 mm, $\gamma_{DR}$ increased from 55% to 75% with a tubular distributor and from 45% to 64% with a plate distributor, while $\gamma_{RD}$ kept almost unchanged at 5%. The solids circulation rate increased with an increase in $d_{or}$. More solids and gas passed through the orifices due to decreasing flowing resistance, which caused an increase in $\gamma_{DR}$. As for $\gamma_{RD}$, there were two opposite effects with increasing orifice diameter. On one hand, the increased circulation rate $G_s$ tended to decrease $\gamma_{RD}$. On the other hand, the increased flowing area through the orifices tended to increase $\gamma_{RD}$. Therefore, $\gamma_{RD}$ changed only slightly even though $G_s$ increased significantly when increasing $d_{or}$. As shown in Fig. 13, $\gamma_{DR}$ with a tubular distributor were slightly larger than that with a plate distributor. This difference can be attributed to the effect of the gas distributor on fluidization quality and the flowing resistance introduced by the tubular gas distributor.

Fig. 13
3.3.3. Effect of draft tube height

The effects of draft tube height $H_R$ on $\gamma_{RD}$ and $\gamma_{DR}$ are shown in Fig. 14. The results with a plate distributor reported in our previous work (Zhao et al., 2011) are included for comparison. It can be seen from Fig. 14 that $\gamma_{DR}$ first increased from 49% to 68% and then decreased to 56% when $H_R$ increased from 235 mm to 295 mm. The gas bypassing was closely related to the solids circulation rate. The pressure difference provides the driving force for both the solids circulation and gas flow from the down-comer to riser. Comparison of Fig. 11 and Fig. 14 shows that $G_s$ and $\gamma_{RD}$ follow the similar trend with increasing $H_R$. The variation of $\gamma_{RD}$ with $H_R$ was opposite to that of $\gamma_{DR}$: with $H_R$ increasing from 235 to 295 mm, $\gamma_{RD}$ increased from 9% to 4% and then decreased to 9%. The values of $\gamma_{RD}$ and $\gamma_{DR}$ with a plate distributor were lower than that with a tubular distributor. The maximum $\gamma_{RD}$ was less than 10%. For the use of producing silicon granules, a smaller $\gamma_{RD}$ indicates a lower reactant concentration and depressed undesired wall deposition in the heating zone. This value can be further decreased by optimizing the draft tube height.

Fig. 14

3.3.4. Correlation of $\gamma_{RD}$ and $\gamma_{DR}$

The gas bypassing fraction in the ICFB with a plate distributor had been correlated by Jeon et al. (2008). In the present study, $\gamma_{RD}$ and $\gamma_{DR}$ in the ICFB with a tubular distributor were correlated by dimensionless equations with $U_R/U_{mf}$ and $U_D/U_{mf}$ as:

$$
\gamma_{RD} = 5.723 \times \left( \frac{U_R}{U_{mf}} \right)^{-0.312} \left( \frac{U_D}{U_{mf}} \right)^{1.115},
$$

(14)

$$
\gamma_{DR} = 5.684 \times \left( \frac{U_R}{U_{mf}} \right)^{1.889} \left( \frac{U_D}{U_{mf}} \right)^{-0.185},
$$

(15)

in the range of $3.53 \leq U_R/U_{mf} \leq 9.87$, $1.10 \leq U_D/U_{mf} \leq 3.89$, with correlation coefficients of 0.962 and 0.928, respectively. The parity plots of $\gamma_{RD}$ and $\gamma_{DR}$ between the experimental and calculated values are shown in Fig. 15. The maximum deviation between the experimental and calculated values of
γRD and γDR are ±20% and ±22%. Again, a reasonable agreement was obtained, showing that Eqs. (14) and (15) can be used to predict the gas bypass fractions.

Fig. 15

4. Conclusions

The solids holdup εs, solids circulation rate Gs and gas bypassing γRD and γDR in an internally circulation fluidized bed were experimentally studied. The effect of the superficial gas velocity UR and UD, orifice diameter dor and height of draft tube HR were investigated. The results lead to the following conclusions:

(1) When the reactor structure and operating parameters changed, the solids circulation rate Gs and gas bypassing from the down-comer to riser γDR followed similar trend, while the variation of γRD was generally opposite to that of γDR.

(2) The superficial gas velocity had a significant effect on both solids circulation rate and gas bypassing. The increase of UR or UD led to an increase in Gs and γDR, and a slight decrease in γRD.

(3) With specific number of orifices, increasing orifice diameter dor led to a notable increase both in Gs and γDR, but had a negligible effect on γRD.

(4) With increasing height of draft tube HR, both Gs and γDR first increased and then decreased, while γRD first decreased and then increased.

(5) The gas bypassing γRD was smaller than 10% in all the operating conditions in this work, and could be further decreased below 5% by optimum design.

(6) Correlations were obtained to predict Gs, γRD and γDR, with a good agreement between the calculated and measured values.

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Notations

\( C_d \)  Particle discharge coefficient
\( d_{or} \)  diameter of orifices on riser, m
\( H \)  distance between two taps of pressure transducers, m
\( h \)  distance between two thermocouple probes, m
\( H_R \)  the height of riser, m
\( G_s \)  solids circulation rate, kg/(m\(^3\)·s)
\( \Delta P \)  pressure drop between two taps of pressure transducers, kPa
\( \Delta P_{or} \)  pressure drop across the orifices, kPa
\( Q_{DR} \)  gas flow rate bypassed from the down-comer to the riser, m\(^3\)/h
\( Q_{D1} \)  gas flow rate injected into the down-comer, m\(^3\)/h
\( Q_{D2} \)  gas flow rate ejected from the down-comer, m\(^3\)/h
\( Q_{RD} \)  gas flow rate bypassed from the riser to the down-comer, m\(^3\)/h
\( Q_{R1} \)  gas flow rate injected into the riser, m\(^3\)/h
\( Q_{R2} \)  gas flow rate ejected from the riser, m\(^3\)/h
\( S_{or} \)  Cross-section area of orifices, m\(^2\)
\( S_D \)  Cross-section area of down-comer, m\(^2\)
\( \Delta t \)  time lag between the two response curves, s
\( U_D \)  gas velocity in down-comer, m/s
\( U_{mf} \)  minimum fluidization gas velocity, m/s
\( U_R \)  gas velocity in riser, m/s
\( u_p \)  average velocity of particles in down-comer, m/s
\( x_{D1} \)  concentration fraction of N\(_2\) injected into the down-comer
\( x_{D2} \)  concentration fraction of N\(_2\) ejected from the down-comer
\( x_{DR} \)  concentration fraction of N\(_2\) bypassed from the down-comer to the riser
\( x_{R1} \)  concentration fraction of N\(_2\) injected into the riser
\( x_{R2} \)  concentration fraction of N\(_2\) ejected from the riser
$x_{RD}$ concentration fraction of $N_2$ bypassed from the riser to the down-comer

$\epsilon_{SD}$ solids holdup of down-comer

$\gamma_{RD}$ gas bypassing fraction from the riser to the down-comer

$\gamma_{DR}$ gas bypassing fraction from the down-comer to the riser

$\rho_p$ density of the solids, kg/m$^3$

$\rho_f$ density of the air, kg/m$^3$

References


Figures

1—riser;
2—down-comer;
3—expanded section;
4—gas distributor;
5—compressor;
6—pressure regulator;
7—valve;
8—gas flow meter;
9—infrared thermometer;
10—solid hopper;
11—bridge circuit;
12—data acquisition system;
13—pressure tap;
14—solid outlet;

Fig. 1. Schematic of the experimental apparatus.
Fig. 2. Typical signals of the infrared temperature probes.
Fig. 3. Typical signals of the gas chromatograph.
Fig. 4. Mass balance for calculation of gas bypassing.
Fig. 5. Effect of superficial gas velocity $U_R$ on solids holdup $\varepsilon_D$ of down-comer.
Fig. 6. Effect of superficial gas velocity $U_D$ on solids holdup $\varepsilon_D$ of down-comer.
Fig. 7. Effect of orifice diameter $d_{or}$ on solid holdup $\varepsilon_{SD}$ of down-comer.
Fig. 8. Effect of draft tube height $H_R$ on solid holdup $\varepsilon_{\text{sd}}$. 
Fig. 9. Effect of superficial gas velocity on solids circulation rate $G_s$. 
Fig. 10. Effect of orifice diameter $d_{or}$ on solids circulation rate $G_s$. 
Fig. 11. Effect of height of draft tube $H_R$ on solids circulation rate $G_s$. 
Fig. 12. Parity plots calculated and measured (a) $\Delta P_{\text{or}}$ and (b) $G_s$. 
Fig. 13. Effect of orifice diameter $d_{or}$ on gas bypassing $\gamma_{RD}$ and $\gamma_{DR}$ with plate distributor and tubular distributor.

Fig. 14. Effect of draft tube height $H_R$ on gas bypassing $\gamma_{RD}$ and $\gamma_{DR}$ with plate distributor and tubular distributor.
Fig. 15. Parity plots of calculated and measured gas bypassing fraction (a) $\gamma_{RD}$ and (b) $\gamma_{DR}$. 
Table

Table 1 Geometry data of the apparatus

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<thead>
<tr>
<th>Parameter</th>
<th>Size (mm)</th>
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<td>Height of reactor</td>
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<tr>
<td>I.D. of riser</td>
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<td>I.D. of orifices on riser</td>
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<td>I.D. of orifices on tubular distributor</td>
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<td>Height of expanded section</td>
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<td>I.D. of expanded section</td>
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<td>Distance between the infrared probes</td>
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