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Friction between gas–solid flow and circulating fluidized bed downer wall

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ABSTRACT

Friction between co-current downflow gas–solid flow and column wall was investigated by measuring apparent and actual solids concentrations in a circulating fluidized bed (CFB) downer. A new model to predict pressure drops due to friction between the gas–solid suspension in the fully developed zone and the downer wall was developed. The results show that the friction between the gas–solid suspension and the downer wall causes a significant deviation of the apparent solids concentrations from the actual ones, especially for those operating conditions with higher superficial gas velocities and solids circulation rates. When the superficial gas velocity is greater than 8 m/s, the actual solids concentrations in the fully developed region of the downer can be up to two to three times of the apparent values. Particle diameters have different influences on the frictional pressure drops under different superficial gas velocity. After the frictional pressure drop is considered, the predicted actual solids concentrations by the proposed model agree well with the experimental values.

1. Introduction

Circulating fluidized bed (CFB) reactors are applied in various types of processes involving gas–solid contact because of their excellent mixing and transport characteristics. As a novel gas–solid reactor, co-current downflow CFB (downer) has been drawing more and more attention due to its advantages over riser. Compared to the riser, the downer exhibits many advantages [1,2]. As the flow of gas–solid suspension in CFB downers has the same direction with gravity, the extent of axial backmixing is reduced greatly in comparison to CFB risers and the flow approaches plug flow conditions. The radial profiles of velocity and solids concentration are also much more uniform across the downer cross-section, in comparison with the CFB riser where significant radial variations in particle velocity and solids concentration are present [3,4]. These advantages are particularly beneficial to processes where extremely short but uniform contact times between gas and solids are required [1], such as the pyrolysis of solid wastes [5], the fluidized catalytic cracking (FCC) [6,7], the coal pyrolysis [8], the biomass pyrolysis [9] and the fast drying of heat sensitive materials [10].

Differential pressure measurements have usually been used to estimate axial profiles of cross-sectional average solids concentrations in CFB risers/downers, assuming that the pressure drops due to gas–solid suspension to wall friction and particle acceleration are negligible. This method has been accepted by many researchers, since it is non-intrusive, inexpensive and simple. However, many experimental results have shown that the contributions of friction and acceleration to the total pressure drop cannot be neglected under certain operating conditions in risers [11–15]. Comparing the actual solids concentration directly measured by a series of quick-closing valves with the apparent values inferred from pressure gradient, Arena et al. [12] found that even in the fully developed zone of the riser, the friction between gas–solid suspension and the riser wall can still lead to significant deviation between the apparent and actual solids concentrations. Van Swaaij et al. [11] found the pressure drop due to friction to be 20–40% of the measured total pressure drops in dilute flows. Wirth et al. [14] found the deviation of the apparent solids concentrations from the actual ones to be about 20%. Hartge et al. [13] found good agreement between the two solids concentrations under lower gas velocities, but particle-wall friction was significant at higher gas velocities. The experimental results of Issangya [15] showed that, under high-density operating conditions, the maximum contribution of frictional pressure loss to the total pressure drop was less than 20%. Rautiainen and Sarkomaa [16] found that when the solids near the riser wall moved downward, the particle friction factor became negative. They also found that particle diameter had great influences on the particle friction factor. Recently, Mabrouk et al. [17] directly tested the particle-wall friction factor and confirmed the importance of the particle-wall friction and further found that the friction factor in the acceleration zone is different from that in the fully developed zone.

Numerous particle-wall friction factor correlations are available in the literature [16,17,18–27] for predicting particle frictional factor

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Nomenclature

d_p	Sauter mean diameter of particles (μm)
D	riser internal diameter (m)
f_g	gas-wall friction factor
f_{g+p}	combined gas–solid friction to wall factor
f_p	particle-wall friction factor
g	gravitational acceleration (m/s^2)
G_m	gas–solid suspension flux (kg/m^2 s)
G_s	solids circulation flux (kg/m^2 s)
H	riser height (m)
P	pressure (Pa)
dP/dz	pressure gradient (Pa/m)
$(dP/dz)_{acc}$	pressure gradient due to gas and solids acceleration (Pa/m)
$(dP/dz)_f$	pressure gradient due to friction between gas–solid suspension and downer wall (Pa/m)
$(dP/dz)_{fg}$	pressure gradient due to gas-wall friction (Pa/m)
$(dP/dz)_{fp}$	pressure gradient due to particle-wall friction (Pa/m)
$(dP/dz)_{static}$	pressure gradient due to gas–solid suspension gravity (Pa/m)
$(dP/dz)_{total}$	measured total pressure gradient (Pa/m)
Re_D	Reynolds number defined as $D\rho_g U_g/\mu_g$
Re_m	Reynolds number defined as $D\rho_m V_m/\mu_g$
U_g	superficial gas velocity (m/s)
V_g	actual gas velocity (m/s)
V_m	actual gas–solid suspension velocity (m/s)
V_p	actual particle velocity (m/s)
z	axial distance (m)

Greek letters

ε_s	solids holdup
$\bar{\varepsilon}_s$	cross-sectional average solids holdup
$\bar{\varepsilon}_{s\ act}$	actual cross-sectional average solids holdup
$\bar{\varepsilon}_{s\ app}$	apparent cross-sectional average solids holdup
$\bar{\varepsilon}_{s\ cal}$	predicted cross-sectional average solids holdup
$\bar{\varepsilon}_{s\,exp}$	experimentally tested cross-sectional average solids holdup
μ_g	gas viscosity (Pa s)
ρ_g	gas density (kg/m^3)
ρ_m	gas–solid suspension density (kg/m^3)
ρ_p	particle density (kg/m^3)

in dilute vertical upward gas–solid flow. However, up to now few works have been conducted to investigate the friction between co-current downflow gas–solid suspension and CFB downer wall. Due to a significant distinction between CFB risers and downers [3] and the fact that all the correlations are merely empirical regression of experimental data, the correlations obtained in the CFB risers cannot be safely extrapolated outside the range of the experimental data.

In this study, a new model to predict the frictional pressure drops has been developed for the fully developed region of CFB downers. At the same time, systematic experimental measurements on the deviation of the apparent solids concentrations from the actual ones in a long downer were carried out to characterize the friction between the gas–solid suspension and the downer wall. Furthermore, many experimental data from the literatures are also used to validate the model.

2. Gas–solid suspension to wall fricition model

2.1. Apparent and actual solids concentration

For a steady co-current downward gas–solid two-phase flow and on the basis of the momentum equation, the pressure drop is expressed as follows:

$$\left(\frac{dP}{dz}\right)_{total} = \left(\frac{dP}{dz}\right)_{acc} + \left(\frac{dP}{dz}\right)_{static} - \left(\frac{dP}{dz}\right)_f \tag{1}$$

where the pressure drops due to acceleration and gravity of the gas–solid suspension are known as

$$\left(\frac{dP}{dz}\right)_{acc} = \frac{d}{dz}\left[\rho_g\overline{(1-\varepsilon_s)V_g^2} + \rho_p\overline{\varepsilon_s V_p^2}\right] \tag{2}$$

$$\left(\frac{dP}{dz}\right)_{static} = \left[\rho_g(1-\bar{\varepsilon}_s) + \rho_p\bar{\varepsilon}_s\right]g \tag{3}$$

When the gas–solid two-phase flow in the riser reaches fully developed state, the acceleration pressure drop $(dP/dz)_{acc}$, should be 0. As a result, the total pressure drop in the fully developed zone consists of only two parts: the static head of gas–solid suspension and the friction pressure loss due to the downer wall friction.

If taking the frictional pressure loss into account, the actual solids concentration, $\bar{\varepsilon}_{s\ act}$, can be evaluated by

$$\bar{\varepsilon}_{s\ act} = \frac{1}{(\rho_p-\rho_g)g}\left[\left(\frac{dP}{dz}\right)_{total} - \rho_g g + \left(\frac{dP}{dz}\right)_f\right] \tag{4}$$

If the frictional pressure loss is neglected, one obtains the apparent solids concentration, $\bar{\varepsilon}_{s\ app}$, by inferring from the measured total pressure gradient

$$\bar{\varepsilon}_{s\ app} = \frac{1}{(\rho_p-\rho_g)g}\left[\left(\frac{dP}{dz}\right)_{total} - \rho_g g\right] \tag{5}$$

Comparing Eq. (4) with Eq. (5), it can be noted that for co-current downward gas–solid flow, the actual solids concentration must be underestimated by the apparent one, since the friction stress exerted on the downer internal wall is contrary to the direction of the gas–solid flow.

2.2. Pressure drop due to friction between gas–solid suspension and downer wall

The friction pressure loss is often separated into two parts due separately to gas alone and to the effect of solid particles

$$\left(\frac{dP}{dz}\right)_f = \left(\frac{dP}{dz}\right)_{fg} + \left(\frac{dP}{dz}\right)_{fp} \tag{6}$$

The pressure drop in gas–solid two-phase flow due to gas-wall friction is assumed to be the same as when only gas is flowing in the same column, which can be expressed by the Fanning equation:

$$\left(\frac{dP}{dz}\right)_{fg} = \frac{2f_g\rho_g(1-\bar{\varepsilon}_s)V_g^2}{D} \tag{7}$$

The gas friction factor, f_g, has been calculated using the Blasius correlation:

$$f_g = \begin{cases} \dfrac{4}{Re_D} & Re_D \le 2300 \\ \dfrac{0.0791}{Re_D^{0.25}} & Re_D > 2300 \end{cases} \tag{8}$$

where the Reynolds number, Re_D, is defined as $(D\rho_g U_g)/\mu_g$.

Similar to the gas-wall friction factor, most investigators (e.g., Konno and Saito [20]; Capes and Nakamura [22]; Yang [24]; Rautiainen and Sarkomaa [16]) have defined the frictional pressure drop due to particle-wall friction following the Fanning equation as

$$\left(\frac{dP}{dz}\right)_{fp} = \frac{2f_p\rho_p\bar{\varepsilon}_s V_p^2}{D} \tag{9}$$

However, the particle-wall friction factor, f_p, is the term in dispute. This factor has been experimental studied by many researchers for pneumatic transport lines and various solids friction factor correlations have been proposed [16,17,18–27].

Since the existence of particles has significant impacts on the gas flow field in gas–solid two-phase flow [28], it is difficult to measure the gas-wall friction and the particle-wall friction separately. Usually, it is the combined friction between gas–solid suspension and column wall that most investigators would measure. As a result, different from the common approach to separately evaluate the gas-wall and particle-wall frictional pressure loss, this study treats the gas–solid two-phase flow in CFB downers as one-dimensional pseudo-homogeneous flow. In this study, the Fanning friction equation for single fluid flow in a pipe is extended to define a combined friction factor between gas–solid suspension and CFB downer wall, f_{g+p}, as

$$\left(\frac{dP}{dz}\right)_{f} = \frac{2f_{g+p}\rho_m V_m^2}{D} \tag{10}$$

where ρ_m and V_m are the cross-sectional average gas–solid suspension density and velocity, respectively. The cross-sectional average gas–solid suspension density ρ_m is known as

$$\rho_m = \rho_g(1-\bar{\varepsilon}_s) + \rho_p\bar{\varepsilon}_s = \rho_g + (\rho_p-\rho_g)\bar{\varepsilon}_s \tag{11}$$

whereas the suspension velocity V_m can be defined differently depending on different purposes. A definition of V_m according to mass conservation is proposed in this study, that is

$$V_m = \frac{G_m}{\rho_m} = \frac{(1-\bar{\varepsilon}_s)\rho_g U_g + G_s}{\rho_g + (\rho_p-\rho_g)\bar{\varepsilon}_s} \tag{12}$$

The combined gas–solid friction factor, f_{g+p}, can also be defined following the Blasius correlation as

$$f_{g+p} = \begin{cases} \dfrac{4}{Re_m} & Re_m \le 2300 \\ \dfrac{0.0791}{Re_m^{0.25}} & Re_m > 2300 \end{cases} \tag{13}$$

where

$$Re_m = \frac{D\rho_m V_m}{\mu_g} = \frac{D[(1-\bar{\varepsilon}_s)\rho_g U_g + G_s]}{\mu_g} \tag{14}$$

Substituting Eqs. (11)–(14) into Eq. (10), one can obtain the frictional pressure drop between the gas–solid suspension and column wall in the fully developed zone of downers

$$\left(\frac{dP}{dz}\right)_{f} = \begin{cases} \dfrac{8\mu_g((1-\bar{\varepsilon}_s)\rho_g U_g + G_s)}{D^2(\rho_g + (\rho_p-\rho_g)\bar{\varepsilon}_s)} & Re_m \le 2300 \\ \dfrac{0.1582\mu_g^{0.25}((1-\bar{\varepsilon}_s)\rho_g U_g + G_s)^{1.75}}{D^{1.25}(\rho_g + (\rho_p-\rho_g)\bar{\varepsilon}_s)} & Re_m > 2300 \end{cases} \tag{15}$$

Obviously, if there is no particle in bed ($G_s = 0$, $\bar{\varepsilon}_g = 0$), Eq. (15) reduces to the Fanning equation for predicting friction pressure drop in a pipe with gas alone.

Consequently, combining Eqs. (4) and (15), one can predict the actual solids concentration in the fully developed zone of CFB downers based on the measured axial total pressure gradient, with given downer diameter, gas and solids properties and operating conditions.

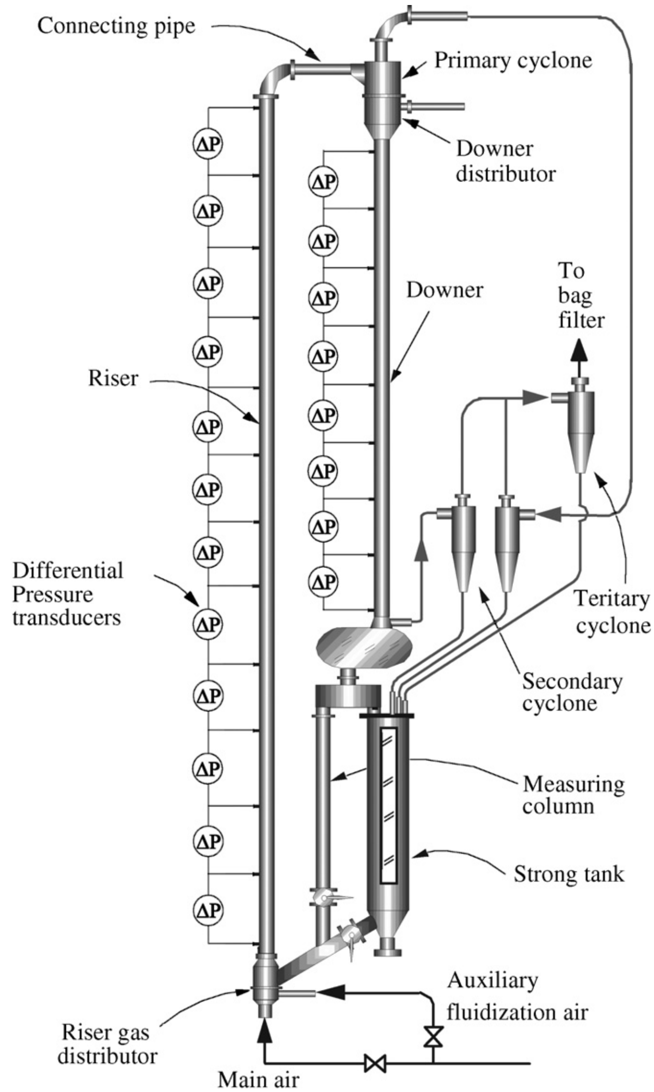

Fig. 1. Schematic diagram of experimental CFB riser/downer system.

3. Experimental apparatus

All experiments were carried out in a cold model CFB downer. The experimental set-up is illustrated schematically in Fig. 1. The downer was 9.3 m in height with 0.1 m i.d. During the operation, main air entered the riser through nozzle tubes and the solids coming from the storage tank were fluidized by the auxiliary air at the riser bottom and then carried upwards by the combination of the auxiliary and main gas stream along the riser column. At the riser top the solids passed a smooth elbow into the primary cyclone at the top of the downer for gas–solid separation, and some escaped solids entered into the secondary and tertiary cyclones for further separation, whereafter the final gas–solid separation was carried out in a bag filter. At the downer top, solids were redistributed by a gas–solid distributor located below the dipleg of the riser primary cyclone. The solids distributor had a small-fluidized bed (held at minimum fluidization) from which particles fell down into the downer through 31 vertically positioned brass tubes. The gas distributor was a plate with 31 holes, located below the solids distributor fluidized bed. Those 31 holes were arranged in the same pattern as the 31 brass tubes in the solids distributor so that the downer fluidizing gas was distributed through the 2 mm gap between the air holes and the brass tubes. From the downer entrance, the co-current downflow gas–solid suspension traveled down through the downer column. After that, the solids were first separated from the air in a quick inertial separator and then drained to the storage tank. The air was further stripped off the entrained particles by two cyclones before it finally passes through the baghouse. Finally, the solids were recycled to the riser bottom from the storage tank, through a butterfly valve located in the inclined feeding pipe. In order to minimize the electrostatics found in both the riser and downer columns, a small stream of steam was introduced into the main air pipeline to humidify the fluidization air to a relative humidity of 50–60%. According to Park et al. [29], at a relative humidity value between 50 and 60%, the electrostatic effects can be controlled in an acceptable level to avoid misleading results.

The particulate materials were spent FCC particles (Sauter mean diameter $d_p = 67\ \mu m$, particle density $\rho_p = 1500\ kg/m^3$). The solids circulation rate was regulated by the butterfly valve and was measured by the measuring pipe.

The fluidization gas used in the study was air at ambient temperature and pressure, supplied by Roots-type blowers. A rotameter was employed to measure the gas flowrate.

As indicated in Fig. 1, eight OMEGA PX series differential pressure transducers were utilized to measure pressure drops along the downer column. According to the measured pressure drop and the corresponding section length, total pressure gradient $(\Delta P/\Delta z)_{total}$, was obtained, and then cross-sectional apparent average solids holdups, $\bar{\varepsilon}_{s\ app}$, were inferred from the obtained total pressure gradients assuming that the pressure drop due to acceleration and friction were negligible.

Reflective-type optical fiber probes are effective tools for measuring the local voidage in fluidized bed reactors, and were widely used by many investigators [30–32]. They yield high signal-to-noise ratios and, if properly designed, they create a minimum disturbance to the overall flow structure [33,34]. More importantly, they are nearly free of interference by temperature, humidity, electrostatics and electromagnetic fields [34–36]. A multi-fiber optical probe, PC-4, developed by the Institute of Process Engineering, Chinese Academy of Sciences, was chosen to measure local solids concentration in this study. The active area of the probe tip with 3.8 mm o.d. is approximately 2 mm × 2 mm, containing approximately 8000 emitting and detecting quartz fibers, each 15 μm in diameter. Because of the non-linear relationship between the voltage signals and the solids concentration in the measurement volume [35], a reliable and precise calibration is vital to an accurate measurement. In this study, a precise calibration was carried out in a specially designed gas–solid downer system, following the calibration procedures detailed by Zhang et al. [35]. Local solids concentrations under 11 operating conditions were measured at 11 radial positions ($(r/R) = 0.0$, 0.158, 0.382, 0.498, 0.590, 0.670, 0.741, 0.806, 0.866, 0.922 and 0.975) on eight axial levels ($z = 0.246$, 0.835, 1.634, 2.548, 3.691, 5.063, 6.435 and 8.036 m). Cross-sectional average actual solids concentrations, $\bar{\varepsilon}_s$, were obtained by integrating the local values at 10 different radial positions excluding the center since 10 of the 11 radial sampling positions had been determined using an area-weighed technique.

In order to ensure the accuracy of solids holdup measurements, preliminary measurements and statistical error analyses were taken for two conditions ($U_g = 7.2$ m/s, $G_s = 101\ kg/m^2\ s$; $U_g = 10.0$ m/s, $G_s = 202\ kg/m^2\ s$) at several axial levels. For each level, 10 measurements were taken for every one of 11 radial positions. The relative standard deviation was found to be within 5%. More details about the experimental system and the measurement instrument can be found in Zhang et al. [3].

4. Results and discussion

4.1. Pressure drop due to friction

Fig. 2 compares the cross-sectional average apparent solids concentrations inferred from the measured total pressure gradients with the actual ones integrated from the local values in the downer under typical operating conditions. The apparent solids concentrations in the downer are seen to be far lower than the actual ones not only in the acceleration zone but also in the fully developed region, especially under operating conditions with higher superficial gas velocity and solids circulating rate. In the acceleration zone of the downer, the closer to the gas distributor, the greater the deviation. This could be explained as follows: since the acceleration direction of gas–solid suspension is the same as gravity, the particles in the acceleration zone of the downer are not fully suspended by the gas and therefore the measured pressure gradient in the acceleration zone is only a small part of the static head of the gas–solid suspension. In the fully developed zone of the downer, since the direction of the frictional pressure drop in the downer is contrary to that of the static head of the gas–solid suspension, the measured total pressure drop must underestimate the static head of the gas–solid suspension.

From Fig. 2, it can also be noted that the deviation of the apparent solids concentration from the actual one increases with superficial gas velocity and/or solids circulation rate. Within the range of this work, at higher superficial gas velocities ($U_g > 10$ m/s), the actual solids concentrations in the fully developed zone of the downer can be up to two times of the apparent ones. For example, as shown in Fig. 2(c), even in the fully developed zone of the downer, the actual solids concentrations are still more than twice of the apparent values. As a result, when the differential pressure measurement method is utilized to estimate the solids concentration in the downer, neglecting the frictional pressure loss in the downer would lead to substantial deviation from the actual solids concentration since the deviation in the fully developed zone of the downer mainly comes from the friction between the gas–solid suspension and the downer wall. This is in line with the deduction of Zhu et al. [1], that one should be very careful when using the differential pressure measurements to estimate the actual solids concentration in a dilute downer given the lower pressure gradient and the relatively high suspension-to-wall friction in the downer.

To further investigate the effects of the solids concentrations on the friction, Fig. 3(a) compares the apparent solids concentrations and the actual ones in the fully developed zone of a high-density downer under different superficial gas velocities (data from Liu et al. [37]). In their experiments, the actual solids concentrations were directly measured by weighing the trapped particles in the downer with a pair of pinch valves [37]. From Fig. 3(a), one can see that under the high-density operating conditions in the downer, although the superficial gas velocities are relatively lower (<6 m/s), the deviation of the apparent solids concentrations from the actual ones is very noticeable. As shown in Fig. 3(a), when $U_g = 5.44$ m/s, the actual solids concentrations can be up to three times of the apparent values, indicating that the friction pressure loss is a more important part of the pressure balance in the high-density downer than that in the low-density downer. Extensively examining Fig. 3(a), one can find that, for a given superficial gas velocity, the absolute deviation of the actual solids concentrations from the apparent ones increases linearly with the solids concentration in the downer. This suggests that the friction between the gas–solid suspension and the downer wall is not only a function of the particle velocity but also the solids concentration. As such, most correlations of particle friction factor for predicting particle-wall friction

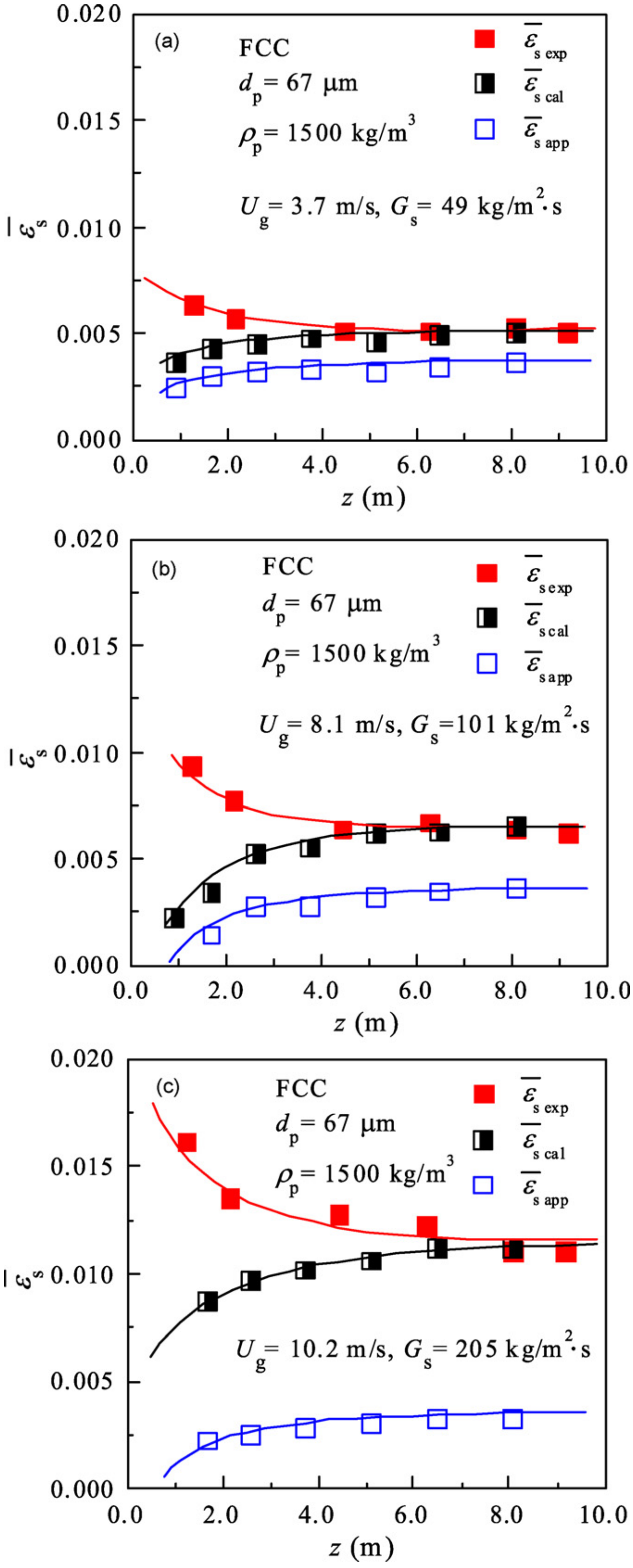

Fig. 2. A comparison of cross-sectional average apparent solids holdups with actual and predicted ones in a low-density downer (H = 9.3 m, D = 100 mm).

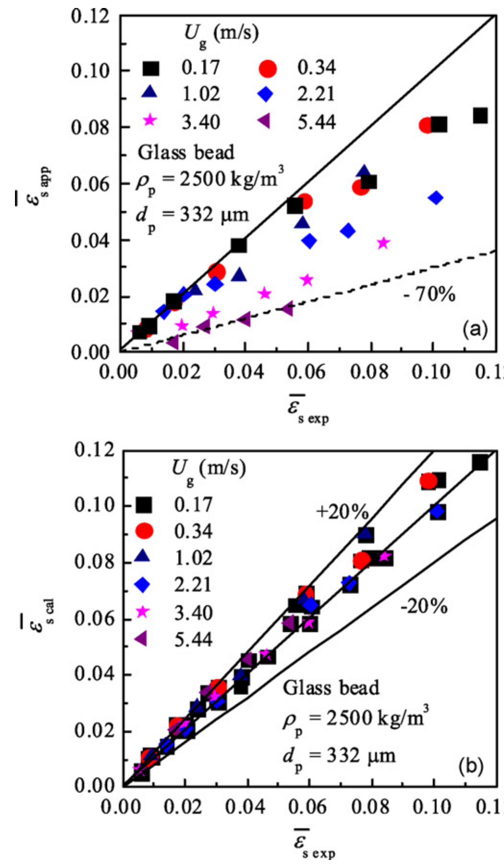

Fig. 3. A comparison of the actual solids concentrations in the fully developed zone of a high-density downer (H = 5.0 m, D = 25.4 mm) with (a) the apparent and (b) the predicted solids concentrations (data from Liu et al. [37]).

in CFB risers in the literature are less accurate since they are only a function of solids velocity.

To quantitatively examine the extent of the pressure drops coming from gas-wall and particle-wall friction, Fig. 4 shows different pressure drops under different superficial gas velocities in the downers. From Fig. 4, it is very clear that the particle-wall frictional pressure losses are significantly larger than those due to gas-wall friction, consistent with the suggestion of Rautiainen and Sarkomaa [16] that it is reasonable to neglect the pressure loss due to gas-wall friction in most case. Comparing the particle-wall frictional pressure drop $(\Delta P/\Delta z)_{fp}$, with the tested overall frictional pressure drop between gas–solid suspension and the downer wall $(\Delta P/\Delta z)_f$, one can find that most frictional pressure drop in co-current downward gas–solid flow in the CFB downers comes from the particle-wall friction. Consequently, when high-density operation is present in a downer, the increased particle-wall friction would lead to a more significant deviation of the apparent solids concentration from the actual one, as indicated by Fig. 4(b).

Its also seen from Fig. 4 that the measured total pressure drops deviate noticeably from the static pressure drops, especially under those operating conditions with higher superficial gas velocities and/or solids circulation rates. This is generally the case for all other runs conducted in this work and by Liu et al. [37]. In the fully developed zone of CFB downers, the large deviation results from the significant frictional pressure drops between gas–solid suspension and the downer wall. Obviously, the deviation is too significant to be neglected, as shown in Fig. 4. For example, in the low-density downer as shown in Fig. 4(a), for G_s = 100 kg/m^2 s and U_g > 8.0 m/s, the static pressure drop $(\Delta P/\Delta z)_{static}$, is greater than

2 times of the measured total pressure drop $(\Delta P/\Delta z)_{total}$. Moreover, the frictional pressure drop $(\Delta P/\Delta z)_f$, is even greater than the measured total pressure drop $(\Delta P/\Delta z)_{total}$. In the high-density downer as shown in Fig. 4(b), for $G_s = 800\ kg/m^2\ s$ and $U_g > 3.4\ m/s$ $(\Delta P/\Delta z)_{static}$ is greater than 3 times of $(\Delta P/\Delta z)_{total}$ and $(\Delta P/\Delta z)_f$ is greater than $(\Delta P/\Delta z)_{total}$. Since the axial pressure gradients in the downer are lower than those in the riser [1], the ratio of the frictional pressure drop to the total pressure drop in the downer is relatively higher than that in the riser. Therefore, a much more significant error may occur if the apparent solids concentrations inferred from the pressure gradient are used to design, scale up and operate downer reactors.

From above, it could be concluded that accurate measurement and prediction of the particle-wall friction pressure loss is of importance in practical model applications for downward gas–solid flow in CFB downers.

4.2. Effects of operating conditions

Examining most correlations of particle-wall friction factor in the literature, one can find that almost all the solids friction factors

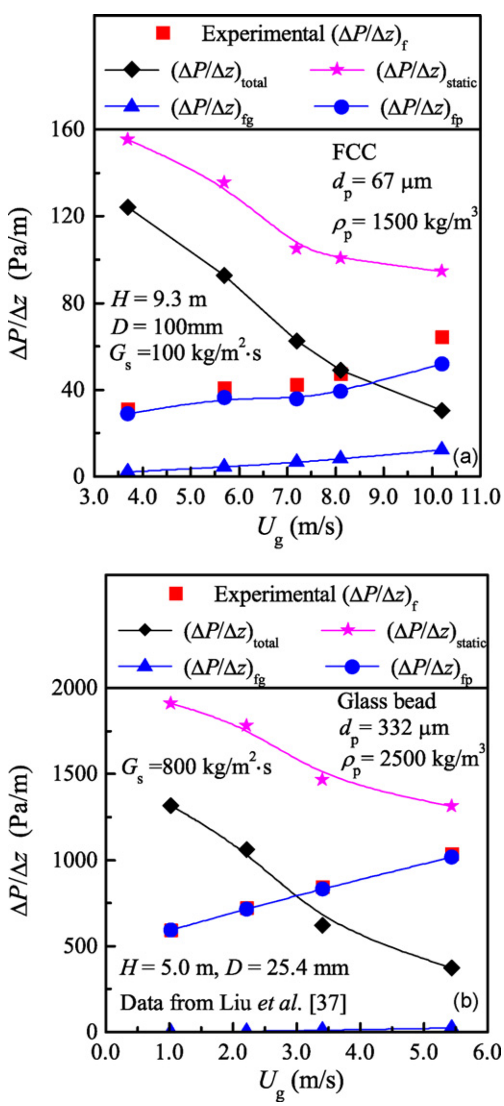

Fig. 4. Comparison between pressure drops under different superficial gas velocities in the low-density downer (a) $H = 9.3\ m$, $D = 100\ mm$ and the high-density downer (b) $H = 5.0\ m$, $D = 25.4\ mm$.

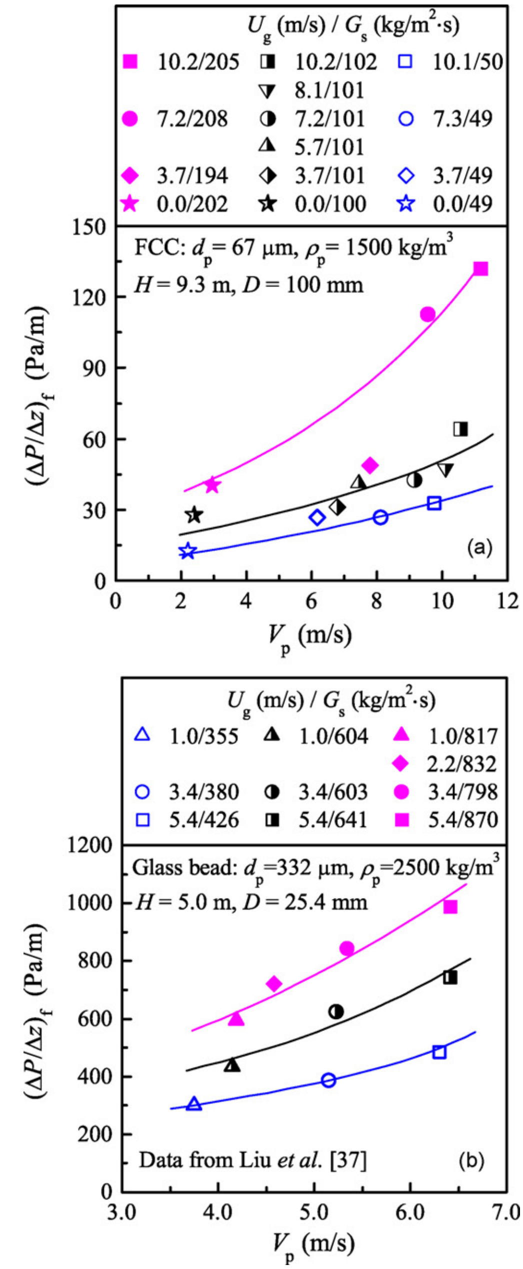

Fig. 5. Effects of operating conditions on the frictional pressure drop in the fully developed region of the low-density downer (a) $H = 9.3\ m$, $D = 100\ mm$ and the high-density downer (b) $H = 5.0\ m$, $D = 25.4\ mm$.

are mainly a function of either solids velocities or solids concentrations. On the other hand, numerous studies have shown that the operating parameters (superficial gas velocity and solids circulation rate) have great influences on the solids concentration distribution and particle velocity in downward gas–solid flow in CFB downers [4,38,39]. Consequently, operating conditions would equally have effects on the friction between gas–solid flow and the downer wall.

Since the frictional particle factor is a function of the solids velocity in most correlations for the frictional particle factor [16,18,20,22,23], Fig. 5 shows the variation of the frictional pressure drop in the fully developed zone of the downers with solids velocity under different operating conditions. Obviously, the frictional pressure drop is not only a function of solids velocity, and the operating parameters also have significant effect on the frictional pressure drop. For the same solids velocity, the friction pressure drops differ

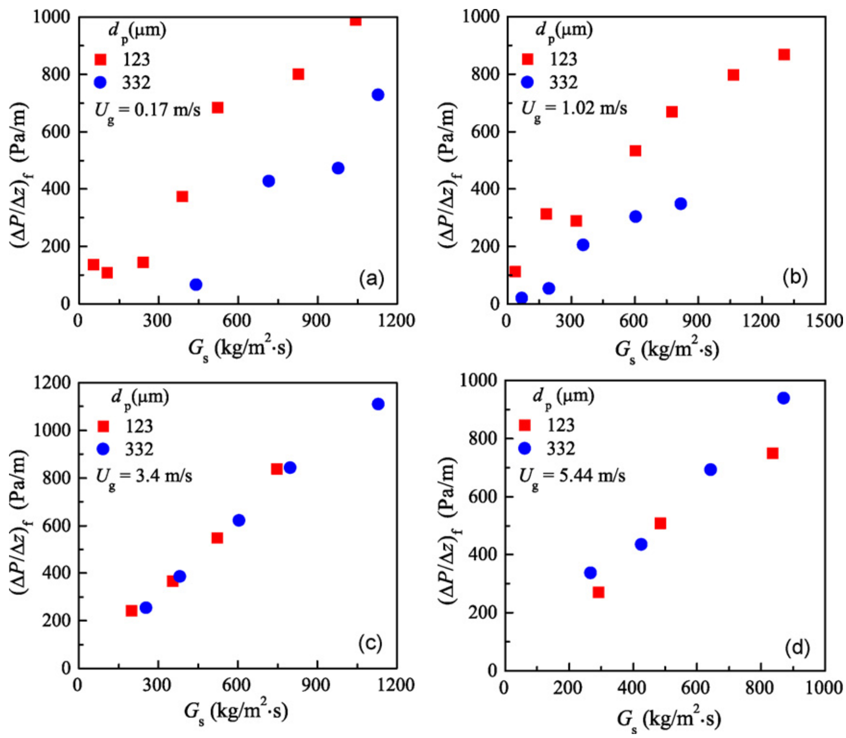

Fig. 6. Effects of particle diameter on the frictional pressure drop in the fully developed section of the high-density downer (H = 5.0 m, D = 25.4 mm) under (a) U_g = 0.17 m/s, (b) U_g = 1.02 m/s, (c) U_g = 3.4 m/s, and (d) U_g = 5.44 m/s (data obtained from Liu et al. [37]).

greatly under different operating conditions. When solids circulation rate remains constant, the frictional pressure drop increases with superficial gas velocity. At a given superficial gas velocity, the frictional pressure drops increase with solids circulation rates. And, with increasing superficial gas velocity, the effect of solids circulation rate on the friction pressure drop gradually becomes more significant. However, there would be many combinations of superficial gas velocities and solids circulation rates that can lead to a given solids velocity. Consequently, correlating the solids friction factor with a single parameter of solids velocity is not enough. The operating condition parameters (i.e. superficial gas velocity and solids circulation rate) should also be included in the correlations of friction factor.

Fig. 3(a) also compares the apparent solids concentrations with the actual solids concentrations in the fully developed section of the high-density downer under different superficial gas velocities. As shown in Fig. 3(a), the operating conditions have great influences on the difference between the apparent and actual solids concentration. The difference between the apparent and actual solids concentration increases with superficial gas velocity for the same actual solids concentration. And, with increasing solids concentration, the effect of superficial gas velocity on the difference between the apparent and actual solids concentration becomes more noticeable. At a given superficial gas velocity, the deviation increases linearly with the solids concentration. Base on these facts, it can be concluded the frictional pressure loss is a function of both the solids velocity and the solids concentration.

4.3. Influences of particle diameters

Many studies have shown that CFB hydrodynamics change with particle properties [40–42], which are expected to also affect the friction pressure loss in CFB downers. The effect of particle diameters on the frictional pressure drops in the fully developed section of the high-density downer under different operating conditions is presented in Fig. 6. Under lower superficial gas velocities as shown in Fig. 6(a) and (b), the frictional pressure losses with smaller particles are greater than those with coarser particles, consistent with the trend inferred from the correlation of Klinzing and Mathur [25], since particles with small diameters are more prone to sticking on the wall. With increasing superficial gas velocity, the influence of particle diameters becomes weak and disappears eventually, as shown in Fig. 6(c) and (d), due to the fact that the ratio of adhesive force to inertial force decreases with increasing of superficial gas velocity

4.4. Validation of the model and comparison with other correlations

Seeing that the model developed in this work is not a simple empirical correlation or regression of experimental data, it could be considered that the frictional pressure drop model can basically characterize the friction between the downward gas–solid flow and the downer wall in the fully developed zone of CFB downers.

As stated above, the friction between gas–solids suspension flow and downer wall causes a significant deviation of apparent solids concentrations from the actual ones. The model can be validated by comparing the actual solids concentrations with the predicted solids concentrations with Eq. (4).

The predicted solids concentration for low density operating conditions by the proposed model developed in this work are plotted in Fig. 2, in comparison with the measured actual solids concentrations integrated from the local ones. A similar comparison under high-density operating conditions is presented in Fig. 3(b). As shown in Figs. 2 and 3(b), after the frictional pressure drop is added to the measured total pressure drop, the predicted solids concentration in the fully developed zone of the downer fits well with the actual solids concentration integrated from the local ones.

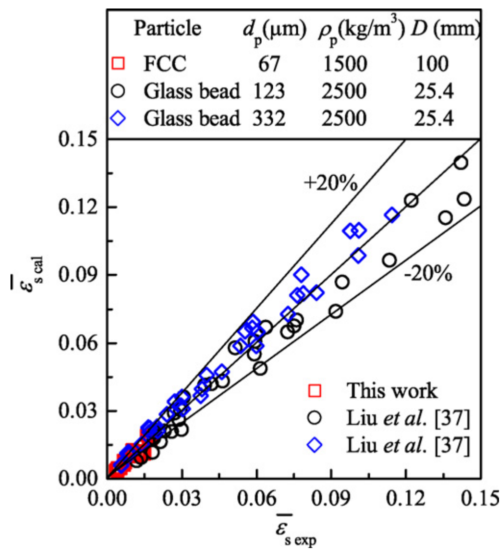

Fig. 7. A comparison of experimental with predicted solids holdups in the fully developed region of the downers.

Moreover, the proposed friction model effectively eliminates the large deviation between the apparent solids concentration and the actual ones. In other words, with the help of this model, the actual solids concentrations in CFB downers can be evaluated by a simple and quick method, differential pressure measurements.

To investigate the reliability of the new model, Fig. 7 compares the predicted solids concentrations by the proposed model with the actual ones obtained in this work and the literature [37]. In all cases, the measured actual solids concentrations agree well with the predicted values. The excellent fit between the predicted solids concentrations and the experimentally measured values obtained from the two different downers over a wide range of operating conditions further shows the reliability of the proposed model. The mean absolute deviation for all the experimental data is 12.4%.

Fig. 8 gives a comparison between the tested frictional pressure drops in the fully developed section of the downer and the predicted values by the proposed model in this work and by other different correlations in the literature. The predictions by the different correlations differ greatly. As shown in Fig. 8, the model proposed in this work and the correlation developed by Yousi and Gau [21] can well predict the frictional pressure losses in the high-density downer by Liu et al. [37]. Only under operating conditions with higher solids velocities, the predictions of the correlations by Konno and Saito [20], Reddy and Pei [18], and Capes and Nakamura [22] are close to the experimental data. The main reason is that the correlations by Konno and Saito [20], Reddy and Pei [18], and Capes and Nakamura [22] are regressed from experimental data obtained from dilute upward gas–solid flow. However, the correlations of Klinzing and Mathur [25] and Kmiec et al. [23] remarkably overestimate the friction pressure losses. The great deviation of the predictions of Klinzing and Mathur [25] can attribute to the difference between the operating conditions in Fig. 8 and the operating conditions of experimental data used to correlate their correlation. The reason for overestimation of the correlation of Kmiec et al. [23] may be that the measuring location is not in the fully developed zone. These indicate that not all the correlations of solids friction factor for upward gas–solid flow can be directly extrapolated to downward gas–solid flow since each correlation has its coverage.

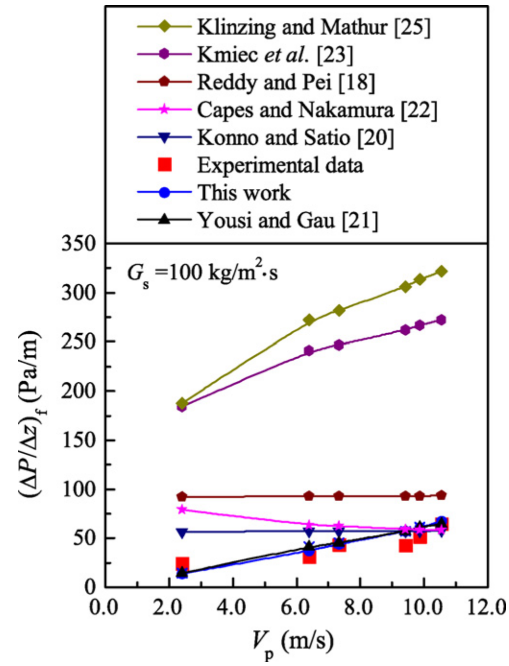

Fig. 8. A comparison of experimental frictional pressure drop in the fully developed region of the high-density downer (Liu et al. [37]) with predicted values by different correlations in the literature.

5. Conclusions

The friction between downward gas–solid suspension flow and column wall inside CFB downers was experimentally investigated by comparing apparent solids concentration and actual ones in the fully developed zone of a 9.3 m high downer. The study on the friction between co-current downward gas–solid flow in the fully developed zone and the downer wall has led to a new model that can successfully predict the pressure loss due to friction between gas–solid suspension and the downer wall in the fully developed zone. By comparing the apparent solids concentrations inferred from measured pressure gradients with the actual ones integrated from local solids concentration measured by an optical probe, it is found that the friction between gas–solid suspension and the wall causes a significant deviation of the actual solids concentration from the apparent one so that it cannot be neglected under certain operating conditions, especially for the downward gas–solid flow with higher superficial gas velocities and/or solids circulation rates. For the downward gas–solid flow in the downers, the actual solids concentration can be up to two to three times of the apparent value under certain operating conditions. The frictional pressure loss is a function of both the solids velocity and the solids concentration. Particle diameters have different effects on the friction pressure loss under different superficial gas velocities. The predicted actual solids concentrations by the proposed model agree well with the experimental values. In general, the friction between the gas–solid suspension and the column wall is an important factor that must be taken into account in the modeling, design and operation of the CFB downer reactors.

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