Solids Holdups in the Fully Developed Region of Circulating Fluidized Beds

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ABSTRACT: The present work focuses on developing correlations for better prediction of solids holdups in the fully developed region of cocurrent upflow and downflow two-phase flow. Systematic experiments were carried out in two CFB risers (15.1m and 10.5m high, respectively, but with the same 0.1 m i. d.) and a 9.3 m high, 0.1 m i. d. CFB downer. The experimental results obtained from about 200 sets of operating conditions, under which the lengths of fully developed section are longer than 2.8 m, show that when the superficial gas velocity is between 3 m/s and 8 m/s, it has a significant effect on the variations of the average solids holdups in the fully developed region with the terminal solids holdups, but when it is less than 3 m/s or greater than 8 m/s, the effect becomes weak and the average solids holdups vary linearly with the terminal solids holdups. By taking into account the effects of superficial gas velocity, particle properties and riser geometry, two empirical correlations for predicting the average solids holdups in the fully developed region of CFB riser and downer were proposed, respectively. These correlations are in good agreement with the experimental data of this work and accords with the correlations reported in literatures.

Keywords：Circulating fluidized beds; Solids holdup; Riser; Downer, Gas/solid flow

1. Introduction

The study of circulating fluidized bed (CFB) riser and downer reactors has received considerable attention in the past few decades because of its importance in various chemical engineering processes, such as coal combustion and fast pyrolysis, fluid catalytic cracking (FCC), fast biomass pyrolysis and drying of heat sensitive materials (Grace, 1990; Lim *et al.*, 1995; Zhu *et al*., 1995, Jin *et al*., 2002). Understanding of the hydrodynamics of CFB reactors is the key to successful design and scale-up of such reactors (Berruti *et al.*, 1995; Zhu, 2005). In particular, solids concentration distribution in CFBs governs the gas-solid contact efficiency, heat and mass transfer rates, and chemical reaction performance (Berruti *et al.*, 1995; Zhu, 2005); consequently it is of great importance to predict the solids concentration in the CFB reactors, especially prediction of solids concentration in the fully developed region of CFB risers and downers is often required in CFB reactor modeling.

Many studies have been carried out to investigate the solids concentration in the fully developed region of CFB risers and a number of correlations to predict average solids holdup in the fully developed region have been proposed. A summary of various correlations in the literatures is given in Table 1. Earlier studies such as Kunnii and Levenspiel (1991) usually assumed the flow in the exit or fully developed region of CFB riser and downer as particulate flow (that is, $\varepsilon_s^*/\varepsilon_s'$ =1). However, given the fact that a uniform dispersion of particles in a gas is always unstable and can lead to formation of particle clusters in a CFB riser/downer (Grace and Tuot, 1979; Krol, *et al*., 2000), it results in higher slip velocity and thus a higher solids holdup for CFB risers and a lower solids holdup for CFB downers. After checking the consistency of CFB experimental data on solids holdups available in the literature, Ouyang and Potter (1993) found that $\varepsilon_s^*/\varepsilon_s'$ =2.6 can correlate the data with a standard deviation of 0.9. Studies of Bai and Kato (1999), Huang *et al* (2001) and Issangya *et al* (2005) have shown that operating conditions and particle properties have influences on the solids concentration in the fully developed region in the CFB risers so that several more general correlations are proposed to improve the prediction accuracy of the correlations.

However, the relationships between the solids holdup and related factors are quite different for these correlations. And, the predictions of different correlations are also not consistent.

When terminal particle concentration ε_s' ($=G_s/(\rho_p(U_g-U_t))$) ranges from 0.01 to 0.05, for the prediction of solids concentration in the dilute region, the predictions of Ouyang and Potter (1993) and Issangya (2005) are 160% higher than the prediction value of Kunii and Levenspiel (1991); the predictions of Bai and Kato (1999) are 94% higher than the prediction values of Kunii and Levenspiel (1991). Obviously, existing experimental data are rather scattered and unable to comprehensively describe the quantitative relation between solids concentration and its relative factors. As a result, many of the correlations are limited to the employed experimental conditions and thus cannot be safely extrapolated outside the range of their experimental data due to the significant scale-up effect of gas/solid two-phase flow in risers (Yan and Zhu, 2004), and the effects of particle properties and operating conditions (Bai *et al*., 1992; Bai and Kato, 1998; Mastellone and Arena, 1999).

Furthermore, most data obtained by the researchers in Table 1 are mainly from risers with the height of less than 10 m. Consequently, even at the top exit of those risers, gas-solid flow may not reach or even not close to fully development. The solids concentrations at the exit of those risers obviously influenced by the riser height and therefore they cannot be used as the solids concentrations in the fully developed region. It is therefore necessary to systematically study the axial distributions of solids holdup in the very long risers.

For CFB downers, few studies have been carried out to investigate the solids concentration in the fully developed region and there is no correlation to predict the solids holdup in the fully developed zone. So, in most gas-solid two-phase downflow model in CFB downers, the terminal solids concentration ε_s' is used as the solids holdup instead of the actual solids concentration in the fully developed region in downers (Deng *et al*., 2004). Numerous experimental results, however, show that the above assumption is not reasonable since there are particle clustering phenomena even in the fully developed region of the downer (Krol *et al*., 2000; Lu *et al*., 2005), especially under the high-density operating conditions (Chen *et al*., 2005). For the purpose of the modeling, design and operation of downer reactors, it is necessary to quantitatively predict the solids concentration in the fully developed region of the downers.

In order to gain new knowledge about the influence of operating conditions, particle properties and riser/downer diameters on the solids concentrations in the fully developed region and obtain a comprehensive correlation for the prediction of the solids holdups in the fully developed zone, this work symmetrically investigates the axial solids distribution and flow development by measure differential pressure distribution in two risers (15.1m and 10.5m in height) and a downer (9.3m in height) with the same internal diameter (100 mm) over a wide range of operating conditions. And, many experimental data from the literatures are also used to validate the correlations.

2. Experimental Apparatus

All experiments were carried out in two cold model circulating fluidized bed systems. The two experimental setups are illustrated schematically in Figure 1. For the CFB riser/downer system, it was designed to incorporate both a riser and a downer and allow the experimental studies on the riser and the downer to be carried out separately or simultaneously. The riser was 15.1 m in height with 0.1 m i.d. and the downer was 9.3 m in height with the same i.d. as the riser, while for the experimental setup II, the riser is 10.5 m long and 100 mm i.d.. To provide acceleration to the solids at the bottom of the riser, a nozzle type gas distributor was employed for both risers. Each gas distributor includes a perforated plate and a bundle of nozzles uniformly installed on the perforated plate. The perforated plate is for auxiliary gas to fluidize the solids from the storage tank while the nozzles are for the main gas to carry the solids upward.

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-solids 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-solids 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 bag filter. Finally, the solids were eventually 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 de-oiled fluidization air to a relative humidity of 70-80%. This has been shown to be very effective.

The fluidization gas used in the study was air at ambient temperature and pressure, supplied by a Roots-type blower. An orifice plate (setup I) or rotameter (setup II) was employed to measure the gas flowrates. The particulate materials were spent FCC (Sauter mean diameter d_p= 67 μm, particle density ρ_p= 1500 kg/m^3) and sand (d_p= 461 μm, ρ_p= 2710 kg/m^3) particles. The FCC particles were used in setup I and the sand particles for setup II.

As indicated in Figure 1, twenty OMEGA PX series differential pressure transducers were utilized to measure pressure drops along the riser and downer column of the setup I. While for the setup II, ten transducers were used along the riser column. According to the measured pressure drop ΔP and the corresponding section length Δz, pressure gradient $\Delta P/\Delta z$ was obtained, and then axial profile of cross-sectional average apparent solids holdups was inferred from the measured pressure gradients based on the assumption that the acceleration of gas and solids and the friction between the gas-solids suspension and the riser wall have negligible effects on the pressure drop. This method has been accepted by many researchers, since it is non-intrusive, inexpensive and simple. Since this study focuses on the solids concentration in the fully developed region, where the acceleration of gas and solids has completed, the apparent solids holdup, therefore, can be used here for this study.

3. Results and Discussion

3.1 Effects of Operating Conditions

Figure 2 (a) and (b) present the solids concentration in the fully developed region of the two risers under different operating conditions. It can be observed from the figures that for a given superficial gas velocity, the solids holdup in the fully developed region increases linearly with solids circulation rates. And, the slope decreases with superficial gas velocity. However, for higher superficial gas velocities (>8 m/s), superficial gas velocity has little influence on the solids holdup. Furthermore, Figure 2 (a) also presents the curve of the saturation carrying capacity for different gas velocities. Obviously, under a given gas velocity, with increasing of solids circulation rate, the transition point of the solids concentrations is not at the corresponding saturation carrying capacity predicted by Bai and Kato (1995), but much larger than that. The reason could be that a nozzle-type gas distributor was utilized in this work to provide fast acceleration of solids at the riser bottom. In a consequence, it should be very careful to use the saturation carrying capacity to divide the relationship between the solids holdup, ε_s^*, and the terminal solids holdup, ε_s' , since the empirical correlation for predicting the saturation carrying capacity does not fit with all experimental condition.

Figure 2 (a) and (b) plot the influence of operating conditions on the solids holdup in the fully developed region of the two downers. Similarly, under a given superficial gas velocity, the solids holdup in the fully developed region increases linearly with solids circulation rates. And, the slope decreases with superficial gas velocity.

After examining all the correlations listed in Table 1, it can be noted that most correlations are mainly correlated with terminal solids holdup. But, for a given terminal solids holdup, there are many combinations of superficial gas velocity and solids circulation rate. In view of the different influences of superficial gas velocity and solids circulation rate, it would be not enough to denote the effect of operating conditions with a simple factor such as terminal solids holdup. To this end, Figure 4 and 5 present the variation of the solids concentrations in the fully developed section of the risers and the downers with terminal solids holdup under different superficial gas velocities, respectively. Obviously, for CFB risers and downers, the slopes of the solids holdup in the fully developed region against terminal solids holdup differ for different superficial gas velocities. This means that the solids holdup, ε_s^*, is not a simple function of the terminal solids holdup, ε_s' , so that it should be more reasonable to include superficial gas velocity when correlating the solids concentration in the fully developed region of CFB riser and downer.

In Figures 4 and 5, the predicted values of the correlations by Kunnii and Levenspiel (1991) and Ouyang and Potter (1993) are also plotted for comparison. As shown in Figures 4 and 5, it is clearly that with increase in superficial gas velocity, the solids concentration in the fully developed region of the risers decreases from the higher boundary (i.e., $\varepsilon_s^*=2.6\,\varepsilon_s'$) predicted by Ouyang and Potter (1993) to the lower one (i.e., $\varepsilon_s^*=\varepsilon_s'$) predicted by Kunnii and Levenspiel (1991). This is consistent with the used experimental conditions or assumption of their correlations. However, for downers, due to the clustering of particles, all the solids concentrations in the fully developed region are less than the terminal solids concentration. With increasing of gas velocity, the gas-solid flow tends to become particulate flow and thus the solids holdup approaches to the terminal solids concentration.

3.2 Influences of Particle Properties

Many studies have shown that many aspects of CFB hydrodynamics change with particle properties (Bai *et al.*, 1992; Mastellone and Arena, 1999). Thereby, particle properties would accordingly affect the solids concentration in the fully developed region of the CFB riser/downer.

Figures 6(a) and (b) present the effect of particle diameter and density on the solids concentration in the fully developed section of a CFB riser, respectively. As shown in Figure 6(a), under the same operating condition in the riser, the solids holdup with coarser particles is slightly higher than that with smaller particles, in disagreement with the experimental results of Bai *et al* (1992) obtained with lower particle density. However, the influence trend of particle density on the solids concentration in the fully developed region is consistent with the finding of Bai *et al* (1992). That is, the increase of particle density results in lower solids concentration in the fully developed region of CFB riser.

Figure 7 shows the effects of particle diameter on the solids holdup in the fully developed region of a high-density downer under different superficial gas velocities. It can be seen from Figure 7 that the influences of particle diameter on the solids holdup are different under different superficial gas velocities. The influence of particle diameter on the solids holdup gradually disappears with increasing of superficial gas velocity. Under lower superficial gas velocities (<4 m/s), the solids concentrations in the downer with larger particles are lower than that with smaller particles, while for higher superficial gas velocities (> 6m/s), particle diameter has no influence on the solids holdup in the fully developed section. This can be explained as follows: since smaller particles are more prone to agglomerate than coarser particles, the extent of particle clustering under lower superficial gas velocities is more significant than that under higher gas velocities so that with decreasing in gas velocity, the effect of particle diameter tends to be more notable.

Of course, the above conclusions need further verification with more experimental results.

3.3 Effects of Riser/downer Diameters

Figures 8 (a) and (b) present the solids holdups in the fully developed zone of the risers and downers with different diameters for FCC particles, respectively. As shown in Figure 8 (a), under the same operating conditions, the solids holdups increase notably with the riser diameters, indicating that the scale of the risers has significant influence on the solids holdup in fully developed region of CFB risers, consistent with the results of Yan and Zhu (2004). Obviously, all correlations listed in Table 1 are not reasonable in this respect. In a consequence, it would lead to considerable deviation if the correlations list in Table 1 are used to design and scale up industrial CFB riser reactors since they are regressed from the experimental data obtained in the lab-scale risers.

However, it can be seen from Figure 8 (b) that the solids holdups in the downers with different diameters under the same operating conditions are almost the same, suggesting that compared with risers, the solids distribution in downers does not change with downer scale. For example, under the same operating conditions, the solids holdups almost keep the same when the downer diameter increasing from 0.025 m to 0.127 m. It can be concluded that within the range of this study, the solids holdup in the fully developed region has no scale up effect in downer diameter. Therefore, it is easier and more reliable to scale up the downer reactors.

To further investigate the scale-up effect in downers, Figure 9 compares the ratios of the solids holdup, ε_s^*, to the terminal solids holdup, ε_s' , in the downers with different diameters for FCC particles. The ratio $\varepsilon_s^*/\varepsilon_s'$ generally illustrates the extent of agglomeration and the slip velocity between solids and gas. It is clearly from Figure 9 that the extents of particle agglomeration are almost the same in the downers with different diameters if the operating conditions keep constant. Also, the ratio increases with superficial gas velocity, which indicates that the gas-solid flow in the fully developed region of the downers gradually approaches particulate flow with increasing of gas velocity. Meantime, it can also be seen from Figure 9 that the relationship between the ratio and superficial gas velocity is not a linear one so that it is not enough to correlate ε_s^* only with ε_s' . Further examining Figure 9, it can be found that even under the higher gas velocity (e.g., U_g=10 m/s), the ratio is only about 0.8, suggesting that there still exist particle clusters in the fully developed region of CFB downers, in line with the results of Krol *et al* (2000) and Lu *et al* (2005).

3.4 Correlation of Solids Holdup in Fully Developed Region

As discussed above, the slope of the solids concentrations, ε_s^*, against the terminal solids concentration, ε_s', changes with superficial gas velocity, so that the terminal particle concentration is not enough for correlating solids holdup in the fully developed region. The influence of superficial gas velocity must be taken into consideration. And, particle diameter and density also have influences on the solids holdups in the fully developed region in the CFB risers and downers. Furthermore, the solids concentrations in the CFB risers under the same operating conditions change significantly with the riser diameters. It seen from the above experimental results that it would lead to significant deviation if the correlations in the literatures listed in Table 1 were extrapolated outside the employed experimental conditions. Consequently, a more general correlation with relatively high accuracy should be developed by taking the effects of operating conditions, particle properties and riser diameters into account.

Based on the correlations in the literatures listed in Table 1, the following correlations are proposed to correlate the experimental data of average solids holdups in the fully developed region of CFB risers and downers, respectively:

$$\varepsilon_s^* = 12.75\left(\frac{G_s}{\rho_p(U_g - U_t)}\right)^{1.25}\left(\frac{U_g}{\sqrt{gD}}\right)^{-0.6} Ar^{-0.05} \tag{1}$$

for CFB risers, and

$$\varepsilon_s^* = 0.125\left(\frac{G_s}{\rho_p(U_g + U_t)}\right)\left(\frac{U_g}{\sqrt{gd_p}}\right)^{0.25} Ar^{0.15} \tag{2}$$

for CFB downers.

A comparison between the predicted values of Equations (1) and (2) and the experimental data is shown in Figure 10 and Figure 11, respectively. It is clearly shown that these correlations fit well with the experimental data obtained from this work and in the literatures. The average relative deviations are ±15.3% (452 points) and ±12.6% (157 points), respectively. The relative deviations are greater than 30% for only a few points. Considering the inevitable divergence among the data in the literatures, the error should be acceptable.

Figure 12 further compares the experimental solids concentrations under different superficial gas velocities with the predicted values by some correlations in Table 1. As shown in Figure 12 (a), (b) and (c), the predicted values of the correlations by Kunii and Levenspiel (1991), Pugsely *et al* (1992), Ouyang and Potter (1993) and Bai and Kato (1999) agree with the experimental solids holdups under different superficial gas velocities, but the prediction value of Equation (1) can fit well with all the solids holdups under different superficial gas velocities. For higher superficial gas velocities (>8 m/s), the experimental solids holdups are in good agreement with the prediction of the correlation by Kunii and Levenspiel (1991), as shown in Figure 12 (a). This could explain as follows: Kunii and Levenspiel (1991) assumed the solids holdup in the upper dilute phase to be particulate flow so that the solids holdup, ε_s^*, equals to the terminal particle concentration, ε_s'. Therefore, their prediction suits for low solids concentration at higher gas velocities. It can be seen from Figure 12 (b) that the predicted values of the correlation by Ouyang and Potter (1993) are almost the same as the measured solids holdups under lower superficial gas velocities (<2 m/s). Since the employed data of their correlation are from short risers with average riser height less than 7.7 m, the gas-solid flow under some most operating conditions are still in acceleration and thus the solids holdup does not reach a constant. Consequently, their prediction is more suitable for high solids concentration conditions. The predicted values of Bai and Kato (1999) is close to the solids concentrations for U_g= 4.5 m/s. This is because their correlation is regressed from the experimental data under the superficial gas velocities ranging from 3.0 to 6.0 m/s.

It can be concluded from the above discussion that the empirical correlations cannot be extrapolated outside the operating conditions ranges of the used experimental data. Although the influence factors such as operating conditions, particle properties and riser diameters have included in Equations (1) and (2), the effect of riser/downer heights on the solids holdup in the fully developed region has not been taken into consideration. So, further experimental investigation and more general correlations are still needed.

4. Conclusions

The solids concentration in the fully developed zone of CFB risers and downers was experimentally investigated by measuring axial pressure gradients profiles in two CFB risers of 15.1 m and 10.5 m high and a CFB downer of 9.3 m high. The experimental results obtained from about 200 sets of operating conditions, under which the lengths of fully developed section are longer than 2.8 m, show that when the superficial gas velocity ranging from 1 m/s to 8 m/s, it has a significant effect on the variations of the average solids holdups in the fully developed region with the terminal solids holdups, but when it is less than 1 m/s or greater than 8 m/s, the effect becomes weak and the average solids holdups vary linearly with the terminal solids holdups. By taking into account the effects of operating conditions, particle properties and riser diameters, two empirical correlations for predicting the average solids holdups in the fully developed region of CFB riser and downer were proposed, respectively. The predicted values by the proposed correlation are in good agreement with the experimental data from this work and the literatures and also explain the differences among the predicted values from correlations proposed by different researchers.

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List of Symbol

Ar	Archimedes Number ($=d_p^3\rho_g g(\rho_p-\rho_g)/\mu_g^2$), (-)
D	riser internal diameter, (m)
d_p	mean diameter of particles, (μm)
G_s	solids circulation rate, (kg/m^2·s)
G_s^*	saturation carrying capacity of gas, (kg/m^2·s)
H	riser height, (m)
$\Delta P/\Delta z$	axial pressure gradient, (Pa/m)
U_g	superficial gas velocity, (m/s)
U_p	superficial solids velocity, (m/s)
U_t	terminal velocity of particle, (m/s)
z	axial position from the riser gas distributor, (m)
	Greek letters
Φ	slip coefficient, (-)
ε_s^*	solids holdup in fully developed region, (-)
$\varepsilon_{s\,cal}^*$	calculated solids holdup in fully developed region, (-)
$\varepsilon_{s\,exp}^*$	measured solids holdup in fully developed region,, (-)
ε_s'	terminal solids holdup ($=G_s/(\rho_p(U_g-U_t))$), (-)
μ_g	gas viscosity, (Pa·s)
ρ_g	gas density, (kg/m^3)
ρ_p	particle density, (kg/m^3)

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Tabble 1. Empirical correlations for predicting the solids holdup in the fully developed region of CFB risers

Author(s)	Correlation
Kwauk *et al*., 1986	$\varepsilon_s^* = 1 - 0.05547\left(\frac{18\,\mathrm{Re}_s^* + 2.7\,\mathrm{Re}_s^{*1.687}}{Ar}\right)^{-0.6222}$
	where $\mathrm{Re}_s^* = \frac{d_p\rho_g}{\mu_g}\left(\frac{U_g}{1-\varepsilon_s^*} - \frac{U_p}{\varepsilon_s^*}\right)$
Gao, 1990	$\varepsilon_s^* = 1 - 1.006\left(\frac{G_s}{\rho_g U_g}\right)^{0.0162}\left(\frac{U_t}{U_g}\right)^{-0.0503}\left(\frac{D}{d_p}\right)^{-0.0259}\left(\frac{d_p\rho_g U_g}{\mu_g}\right)^{-0.02527}$
Kunii and Levenspiel, 1991	$\varepsilon_s^* = \frac{G_s}{\rho_p(U_g - U_t)}$
Pugsely *et al*., 1992	$\varepsilon_s^* = \frac{2G_s}{\rho_p U_g + 2G_s}$
Wong *et al*., 1992	$\frac{\varepsilon^*}{1-\varepsilon^*} = 130.93\left[U_g\left(\frac{\rho_g^2}{\mu_g(\rho_p - \rho_g)}\right)^{1/3}\right]^{-0.86}\left(\frac{G_s}{\rho_p(U_g - U_t)}\right)^{-0.30} D^{-0.54}\left(\frac{d_p\rho_g U_t}{\mu_g}\right)^{-0.10} z^{10.34}$
Patience *et al*., 1992	$\varepsilon_s^* = \frac{\Phi G_s}{\rho_p U_g + \Phi G_s}$
	where $\Phi = 1 + 5.6\frac{\sqrt{gD}}{U_g} + 0.47\left(\frac{U_t}{\sqrt{gD}}\right)^{0.41}$

Tabble 1. Empirical correlations for predicting the solids holdup in the fully developed region of CFB risers (continued)

Author(s)	Correlation	
Ouyang and Potter, 1993	$\varepsilon_s^* = 2.6 \dfrac{G_s}{\rho_p (U_g - U_t)}$	
Bi and Zhu, 1993	$\varepsilon_s^* = \dfrac{G_s^*}{\rho_p (U_g - U_t)}$	
	where $\dfrac{U_g}{\sqrt{g d_p}} = 21.6 \left(\dfrac{G_s^*}{\rho_g U_g} \right)^{0.542} Ar^{0.105}$	
Bai and Kato, 1999	$\varepsilon_s^* = 4.04 \left(\dfrac{G_s}{\rho_p (U_g - U_t)} \right)^{1.214}$	$(G_s < G_s^*)$
	$\varepsilon_s^* = \dfrac{G_s}{\rho_p (U_g - U_t)} \left[1 + 0.208 \left(\dfrac{\rho_p U_g}{G_s} \right)^{0.5} \left(\dfrac{\rho_p - \rho_g}{\rho_g} \right)^{-0.082} \right]$	$(G_s \geq G_s^*)$
Huang *et al*., 2001	$\varepsilon_s^* = 33.684 \dfrac{G_s}{\rho_p (U_g - U_t)} \left(\dfrac{U_g}{\sqrt{g d_p}} \right)^{-0.6} + 0.00184$	
Issangya *et al*., 2005	$\varepsilon_s^* = 5.06 \left(\dfrac{G_s}{\rho_p (U_g - U_t)} \right)^{1.19} Ar^{-0.05}$	

Table 2. Experimental conditions for the data in the literatures

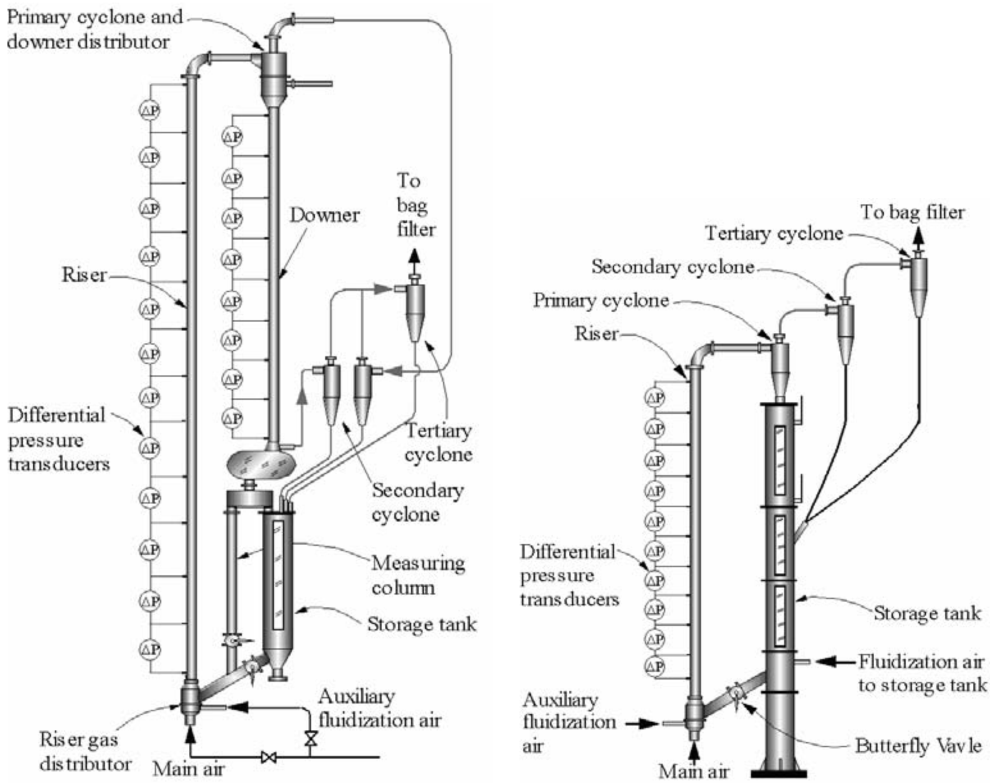
Investigator(s)	H (m)	D (m)	Particles	d_p (μm)	ρ_p (kg/m^3)	U_g (m/s)	G_s (kg/m^2·s)	Data points	Symbols in Figure 10
This work	15.3	0.1	FCC	67	1500	2.0~10.3	10~230	163	□
	10.5	0.1	sand	461	2710	4.6~11.5	20~215	61	×
Yan and Zhu, 2004	10.0	0.203	FCC	67	1500	3.5~8.0	40~200	22	○
Parssinen and Zhu, 2001	10.0	0.076	FCC	67	1500	3.5~10.0	50~550	9	◇
Issangya, 1998	6.1	0.076	FCC	70	1600	4.0~8.0	68~425	9	☆
Mastellone and Arena, 1999	5.75	120	FCC	70	1770	3.0~3.5	35~110	3	▷
	5.75	120	Silica sand	310	2600	5.0~6.0	16~120	12	△
	5.75	120	Ballotini#1	67	2540	3.5	80~130	2	▽
	5.75	120	Ballotini#2	89	2540	3.0~6.0	15~250	14	◁
Ouyang and Potter, 1993	10	0.254	FCC	65	1380	2.3~7.5	54~206	14	⊙
Li and Kwauk, 1980	8.0	0.09	Iron ore	105	4510	4.0~7.0	82~157	16	■
	8.0	0.09	Alumina	81	3090	1.8~5.6	35~140	13	◢
	8.0	0.09	FCC	58	1780	0.8~3.0	12~35	14	◥
	8.0	0.09	Pyrite Cinder	56	3050	1.5~3.0	72~129	8	◤
Bader *et al.*, 1988	12.2	0.305	FCC	76	1714	4.3, 9.1	147	2	⊗
Bi *et al.*, 1989	8.0	0.186	Silica gel	280	706	3.7, 6.0	42~134	5	⊕
Yang *et al.*, 1984	8.0	0.115	Silica gel	220	794	5.3	43~160	4	⊖
Arena *et al.*, 1991	5.75	0.12	Ballotini	90	2543	5.0	92~251	3	⊠

Table 2. Experimental conditions for the data in the literatures (continued)

Investigator(s)	H (m)	D (m)	Particles	d_p (μm)	ρ_p (kg/m^3)	U_g (m/s)	G_s (kg/m^2·s)	Data points	Symbols in Figure 10
Weinstein *et al.*, 1984	8.5	0.152	HFZ-20	49	1520	2.9, 3.4	71~140	10	□
Horio *et al.*, 1988	2.79	0.05	FCC	60	1000	1.17~1.29	11~14	3	□
Contractor *et al.*, 1991	NA	0.15	FCC	70	1570	5.7	294~685	4	□
Hartge *et al.*, 1986	3.3	0.05	sand	56	2600	3.4~4.0	71~90	3	□
	7.8	0.4	sand	56	2600	4.2~5.0	64~118	3	□
Yerushalmi *et al.*, 1979	7.2	0.076	FCC	60	881	2.4~4.6	50~212	3	□
Yerushalmi and Avidan, 1985	8.5	0.152	HFZ-20	49	1450	1.9~4.1	113~173	4	□
Rhodes and Geldart, 1986	6	0.152	9G	64	1800	2.5~4.5	8.5~107	4	□
	6	0.152	sand	270	2600	6.0~8.0	70~160	4	□
Louge and Chang, 1990	7.0	0.203	FCC	72	1300	2.0	40	1	▲
Li *et al.*, 1988	10	0.09	FCC	54	930	1.5~2.1	14~193	11	□
Bai and Kato, 1995	3.0	0.06	FCC	59	1623	1.5~3.0	8~38	8	□
	3.0	0.097	FCC	59	1623	1.5~3.0	10~64	10	●
	3.0	0.15	FCC	59	1623	1.5~2.5	18~88	10	□

Table 3. Experimental conditions for the data in the literatures

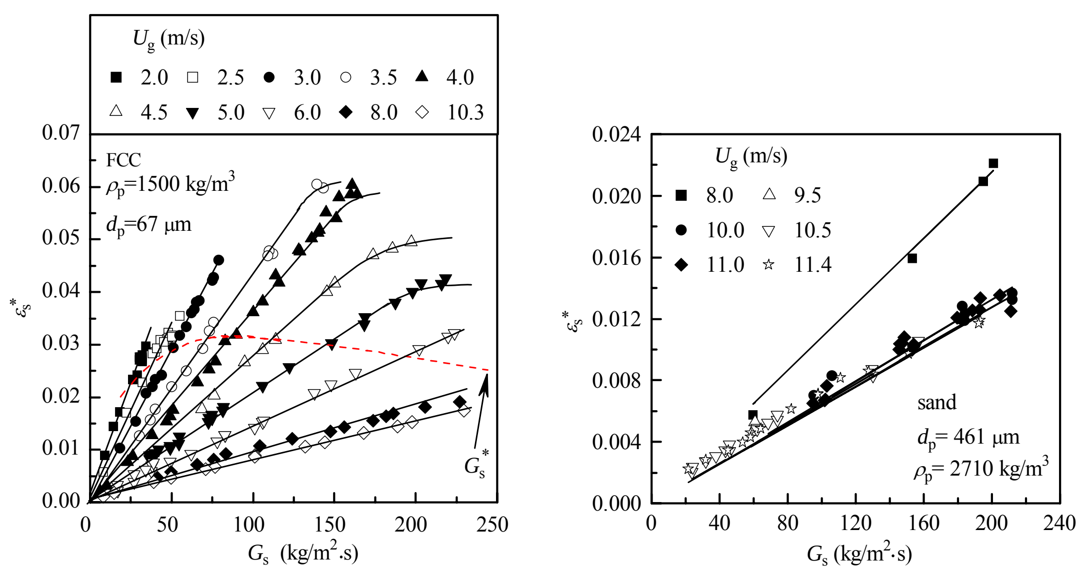
Investigator(s)	H (m)	D (m)	Particles	d_p (μm)	ρ_p (kg/m^3)	U_g (m/s)	G_s (kg/m^2·s)	Data points	Symbols in Figure 11
This work	9.3	0.1	FCC	67	1500	3.7~10.2	49~205	11	□
Chen and Li, 2004	5.6	0.08	Silica gel A	572	750	1.65	45~345	7	▲
			Silica gel B	128	750	1.05	26~258	6	□
			FCC	82	992	0.8	45~240	6	▼
			Glass beads	131	2480	1.1	70~552	7	□
Liu *et al.*, 2001	5.0	0.025	FCC	70	1300	1.02~7.82	16~387	27	■
			Glass beads	123	2500	0.17~7.82	21~1397	31	□
			Glass beads	332	2500	1.02~7.82	66~1340	28	□
Wang *et al.*, 1992	5.8	0.14	FCC	59	1545	4.33~7.94	67~165	7	●
Qi *et al.*, 1990	5.8	0.14	FCC	59	1545	4.33~6.14	100	2	○
Herbert *et al.*, 1998	4.6	0.05	FCC	75	1630	0.4~6.1	92	5	□
Schiewe *et al.*, 1999	8.6	0.15	Glass beads	125	2480	3.6~6.6	50	2	□
Cao and Weinstein, 2000	4.6	0.127	FCC	82	1480	2.9~3.7	51~236	5	□
Johnston *et al.*, 1999	9.3	0.1	FCC	67	1500	5.2~9.5	45~180	6	□
Tuzla *et al.*, 1998	8.6	0.15	Glass beads	125	2500	1.0~6.0	51~89	2	×
Yang *et al.*, 1995	5.8	0.14	FCC	59	1545	4.33~6.14	65~138	5	◀



(a) setup I: CFB riser (0.1m i.d./15.1 m height) and downer (0.1m i.d./9.3 m height)

(b) setup II: CFB riser (0.1m i.d./10.5 m height)

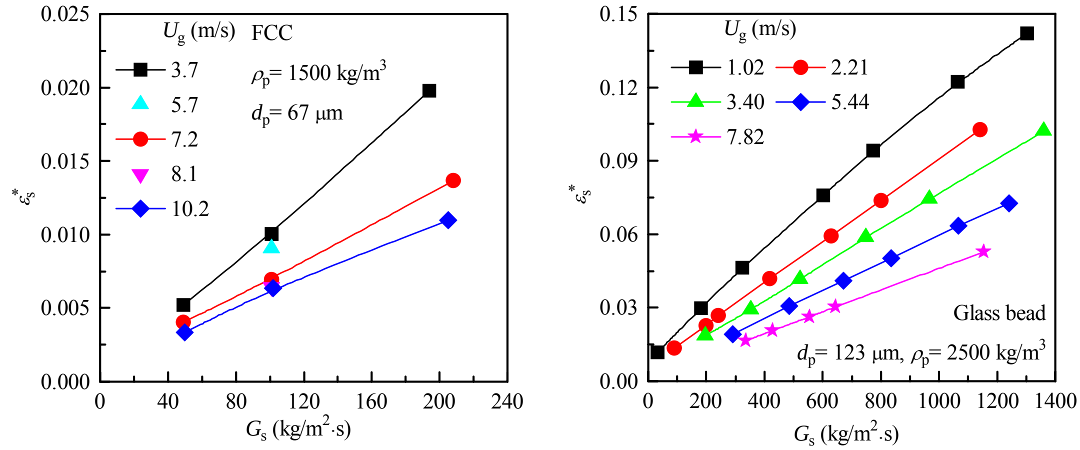
Figure 1. Schematic diagrams of the CFB systems



(a) H=15.1m, D =0.1m

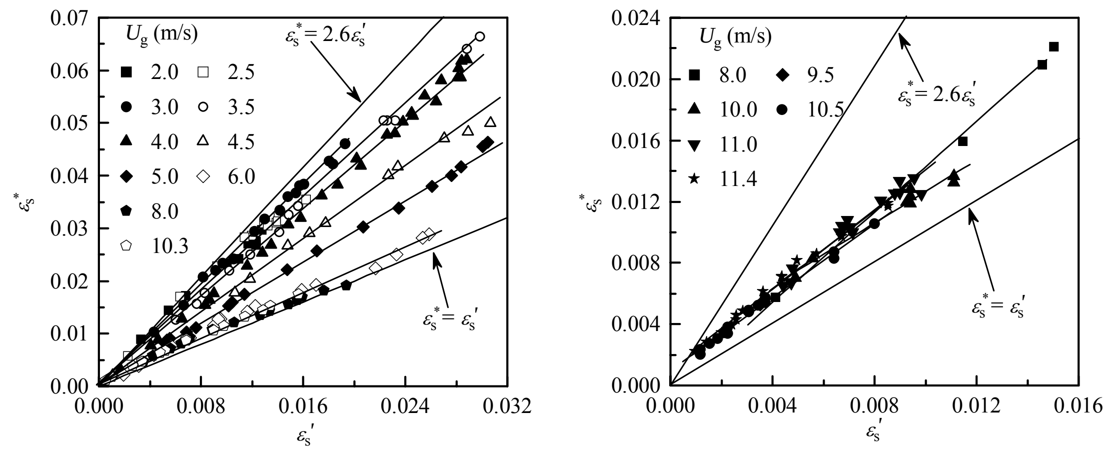
(b) H=10.5m, D =0.1m

Figure 2. Solids concentrations in the fully developed zone of the risers under different operating conditions (the dash line indicates the saturation carrying capacity of the corresponding superficial gas velocity calculated by Bai and Kato, 1995)



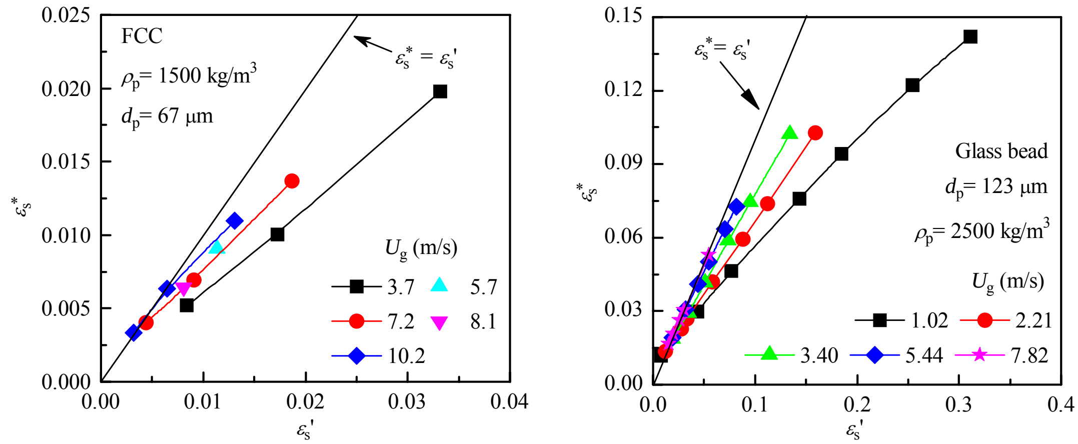
(a) H=9.5m, D =0.1m (b) H=5.0m, D =0.025m (data from Liu, 1999)

Figure 3. Solids concentrations in the fully developed zone of the downers under different operating conditions



(a) H=15.1m, D =0.1 m (b) H=10.5m, D =0.1 m

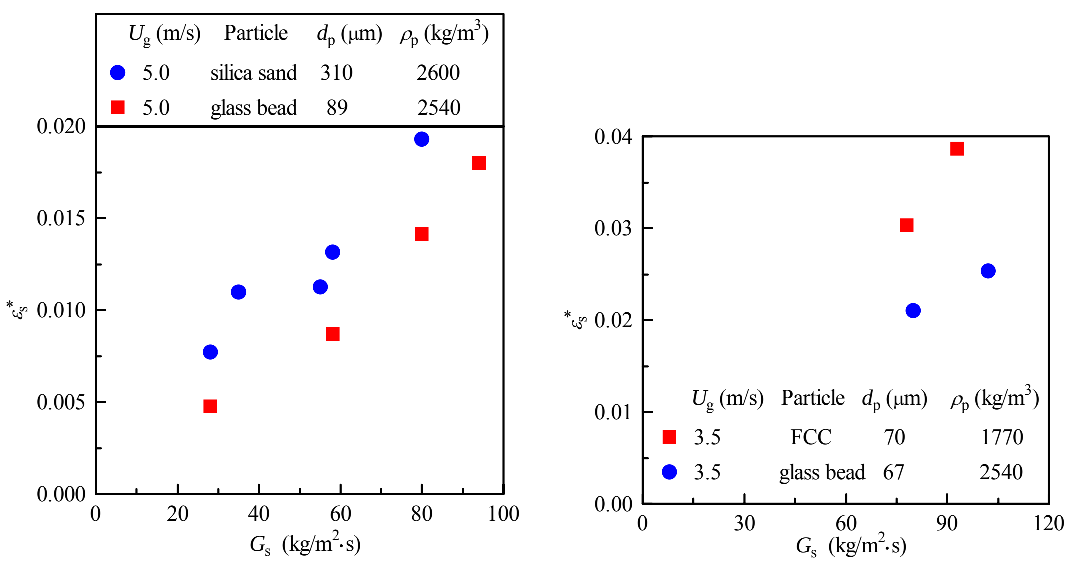
Figure 4. Variation of solids holdups in the fully developed zone of the risers with terminal solids holdup under different superficial gas velocities



(a) H=9.5m, D =0.1m

(b) H=5.0m, D =0.025m (data obtained from Liu, 1999)

Figure 5. Variation of solids holdups in the fully developed zone of the downers with terminal solids holdup under different superficial gas velocities



(a)

(b)

Figure 6. Effect of (a) particle diameter and (b) particle density on the solids holdups in the fully developed zone of the riser (data obtained from Mastellone and Arena, 1999)

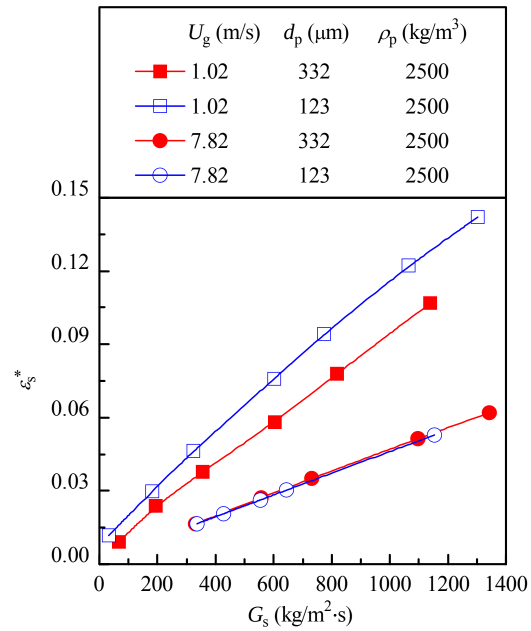


Figure 7. Effect of particle diameter on the solids holdup in the fully developed region of the downer (data obtained from Liu, 1999)

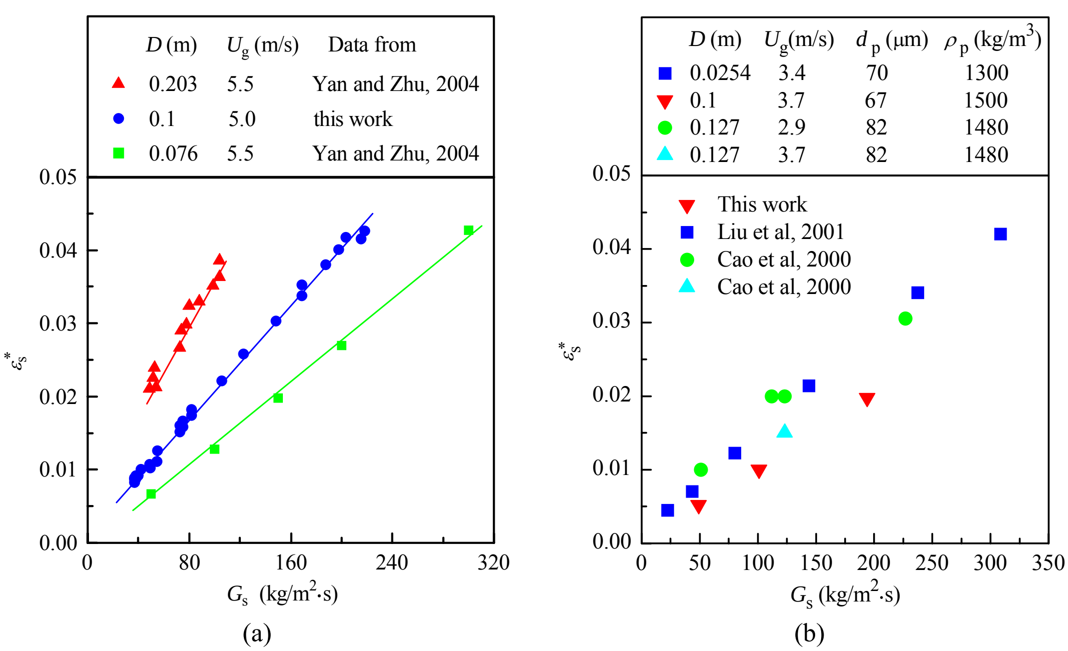


Figure 8. Solids holdups in the fully developed region of the (a) risers and (b) downers with different diameters for FCC particles

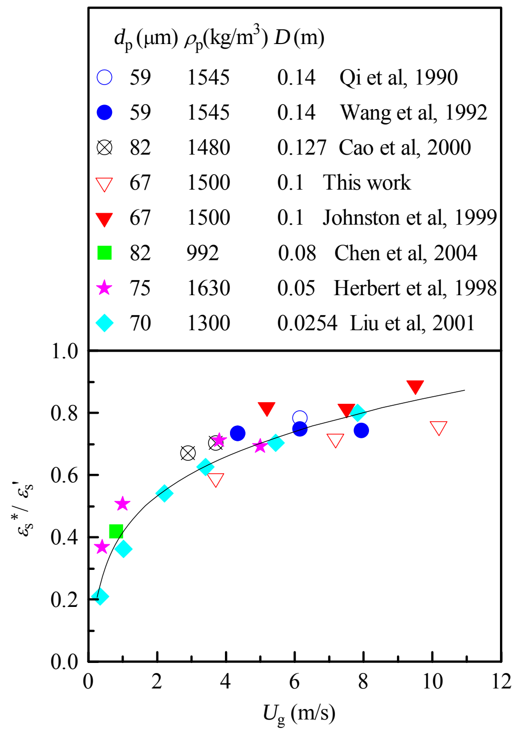


Figure 9. Ratio of solids holdup in the fully developed region to terminal solids holdup in the downers with different diameters for FCC particles

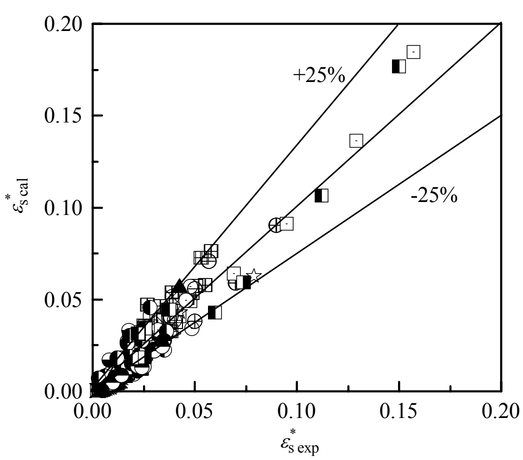


Figure 10. A comparison of the predicted values by equation (1) with experimental solids holdups in the fully developed region of the risers (the symbols are indicated in Table 2)

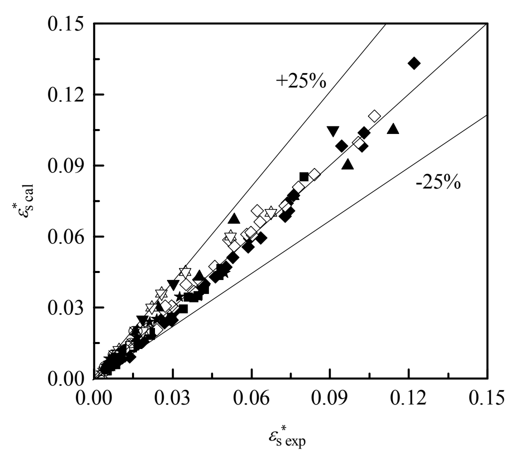
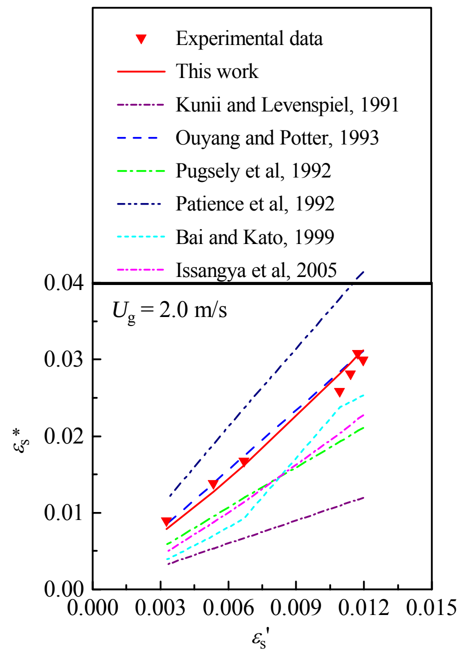
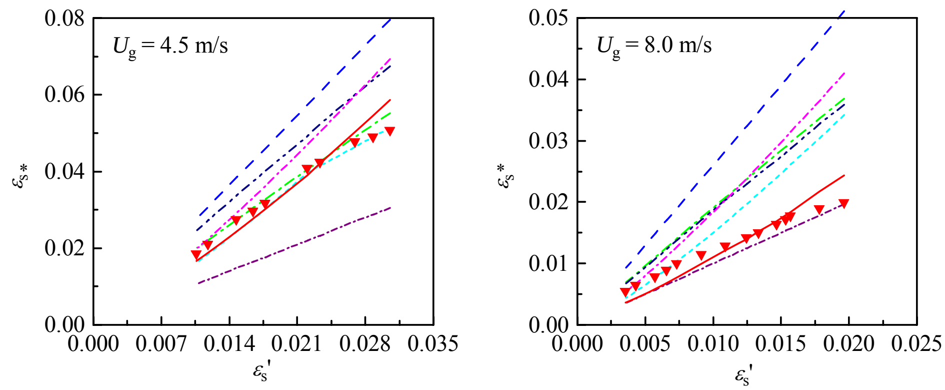


Figure 11. A comparison of predicted values by equation (2) with experimental solids holdups in the fully developed region of the downers (the symbols are indicated in Table 3)



(a) U_g = 2.0 m/s



(b) U_g = 4.5 m/s (c) U_g = 8.0 m/s

Figure 12. A comparison of experimental solids holdups in the fully developed zone of the riser with predicted values by correlations of this work and in the literatures