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Chemical Engineering Journal 92 (2003) 161–167

Chemical Engineering Journal

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The near wall dense ring in a large-scale down-flow circulating fluidized bed

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Accepted 22 July 2002

Abstract

Radial profiles of local solids fraction at different axial positions were obtained through a dual-optical density probe in a 0.418 m ID and 18 m high large-scale circulating fluidized bed (CFB) downer under different operating conditions. Radial distribution of local solids fraction in large-scale downer is uniform in the central region but a relatively high concentration dense ring exists near the wall. The near wall dense ring is a typical characteristic in the downer and exists under all the examined operating conditions. Although the peak value and its radial position of the near wall dense ring will slightly change with operating conditions, the overall shape of radial solids fraction profiles remains unchanged. The absolute distance from the radial position of the peak value of solids fraction to the wall is relatively constant in different scale downers, and the proportion of the area of core region where solids distributed uniformly to the whole cross-section increases with the scale-up of downer. Experiments were carried out in a specially designed wall structure, and results show that the existence of the near wall dense ring is related with the wall of downer.

Keywords: CFB downer; Solids fraction distribution; Dense ring; Large-scale

1. Introduction

Nowadays, more and more attention has been paid to a new type of gas–solids reactor, the cocurrent down-flow circulating fluidized bed (CFB downer). Compared to the conventional CFB riser reactor, it has many advantages such as much more uniform gas–solids flow with less aggregation, less gas and solids back mixing, and shorter residence time. These excellent characteristics are especially beneficial to the process that requires short and uniform residence time distribution for the gas and solids phase to decrease the by-products and over-reacting [1]. Potential application fields for the downer reactor are the fluidized catalytic cracking (FCC) [2–5], ultra-pyrolysis of cellulose [6], coal gasification [7], residual oil fluidized catalytic cracking (RFCC), and even carbon nanotubes (CNTs) production [8].

Radial distribution of local solids fraction is an important behavior which links with the hydrodynamics of gas–solids flow, the transfer of heat and mass, as well as the scale-up of the downer reactor. In the last decade, many investigations have been done to the radial solids fraction distribution in the downer. Herbert et al. [9] found that in a 50 mm diameter downer, solids distributed uniformly in the center region, while a relatively dense ring exists at $r/R = 0.7$. Experiment results in a downer with 140 mm ID at Fluidization Lab of Tsinghua University (FLOTU) show a flat core region and a peak around $r/R = 0.94$ in the radial profiles of local solids fraction [10–13]. Similar radial distribution shape of local solids fraction in the downer was also reported by Lehner and Wirth [14,15] in a 150 mm downer. However, radial solids distributions in the fully developed section in a downer with 100 mm diameter are a little different: the radial profiles of solids fraction are fairly uniform distribution, with a very flat core region ($r/R < 0.7$–0.8) and somewhat decreasing solids holdup towards the wall in the annular region [16,17]. Cao and Weinstein's [18] studies in a 127 mm diameter downer show that the maximum value of solids fraction in radial distribution is just at wall ($r/R = 1$), and similar results were also reported by Cheng et al. [19] in a 92 mm downer. The inconsistence of radial solids fraction profiles obtained by different investigators focuses on the near wall region of the downer. The near wall region of the downer should be paid more attentions for not only the solids fraction distribution in which is quite different from that in the center, but the heat and mass transfer between the wall and the gas–solids suspension in the downer reactor is reasonably related with this region.

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PII: S1385-8947(02)00191-2

Nomenclature

D	distance from the wall of downer (mm)
G_s	solids mass flux (kg/m^2 s)
H	measuring position, the distance below the gas distributor in the downer (m)
N	output signal of the dual-optical density probe
r	radial coordinate of the measuring point (mm)
r/R	relative radius of the measuring position, in the central $r/R = 0$ and in the wall $r/R = 1$
R	radius of the downer (mm)
U_g	superficial gas velocity (m/s)

Greek letters

ε	gas fraction
$\bar{\varepsilon}$	cross-sectional average air fraction

Although many investigations have been given to the radial distribution of solids fraction in the downer, most of the experiments were conducted in the reactor with diameter not more than 150 mm. Since the particle velocity in the downer is much higher than that in a riser under the same superficial gas velocity [17], the diameter of the downer should be large enough to catch up with the same handling capacity of the riser for the same kind of catalyst. Hence it is very important to study the solids fraction distribution in the large-scale downer for the potential industry applications. The objectives of this work are investigating radial solids profile in a 0.418 m ID large-scale downer and exploring the solids distribution behavior in the near wall region.

2. Experimental

2.1. The CFB apparatus

The CFB experiment rig used in the present work is (see Fig. 1) a semi-industrial plant. It consists of an 18 m high circular riser with an inner diameter of 0.418 m and a circular downer with same inner diameter and 6.5 m length. Experiments were conducted at ambient temperature and pressure. The operating superficial gas velocity, U_g, and mean solids flux, G_s, are 1.8–10 m/s and 19–180 kg/m^2 s, respectively. The fluidized gas used in all experiments was air, and spent FCC catalyst with 77 μm mean diameter and 1398 kg/m^3 density was used as fluidized particle. The measuring position H represents the length below the gas distributor in the downer.

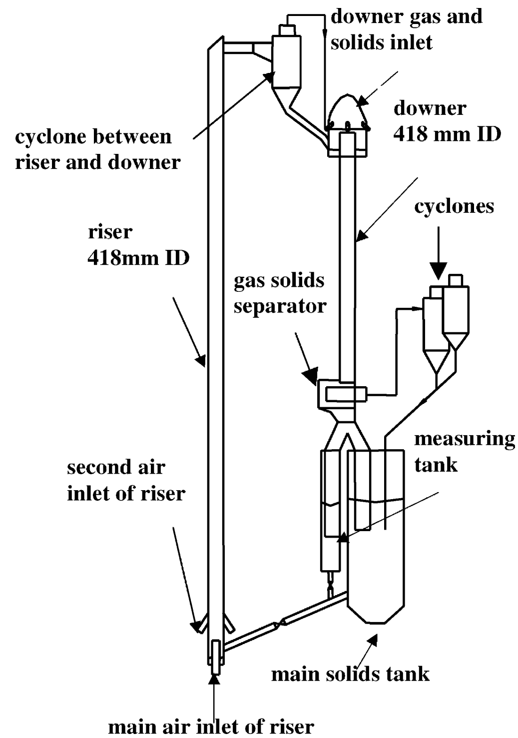

Fig. 1. Schematic diagram of apparatus.

2.2. Solids fraction measuring system

A dual-optical density probe was used to obtain the transient signals of local solids fractions in the bed, as shown

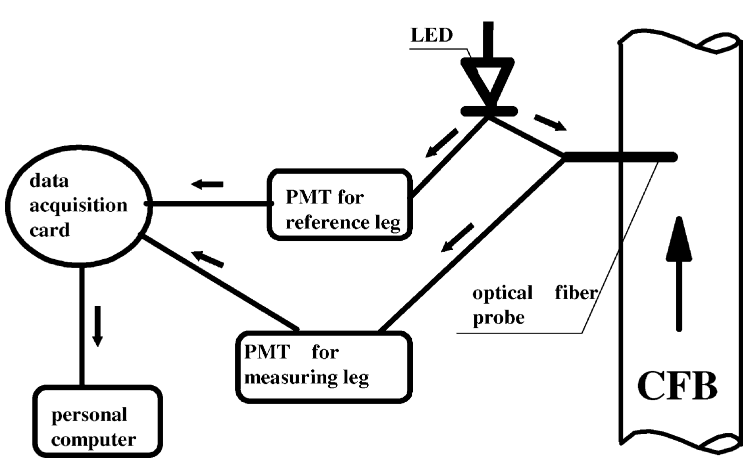

Fig. 2. Schematic diagram of dual-optical density probe.

in Fig. 2. A double light legs system, a reference leg and a measuring leg, is used to reduce the effects of any photomultiplier tube (PMT) instability. Data acquisition system records the reference and measuring light signals from two PMT detectors at the same time. The ratio of the two signals, N, is chosen as the measured solids fraction signal. This improvement guarantees the deviation of the signal under 0.1% within 5 h. The front tip of the probe is $2 \times 2\,\text{mm}^2$ ensuring that the measurements reasonably represent the solids fraction of passing elements without causing much disturbance to the flow. The calibration method to determine the relationship between the output signal and the solids fraction in the bed is similar to that of Lin et al. [20]. The relationship between the density signal output, N, and solids fraction can be well fitted by the following Boltzmann function:

$$1 - \varepsilon = \frac{0.00446 - 0.684}{1 + \exp((N - 0.691)/0.0608)} + 0.684 \qquad (1)$$

3. Results and discussions

3.1. Radial profiles of solids fraction in 0.42 m diameter downer

Radial profiles of solids fraction at different axial positions in the full-developed section of the downer were shown in Fig. 3. A specially designed dense turbulent gas–solids distributor was used in this work, so it can reach the typical uniform radial distribution in a relatively short distance (only 1.2 m from the gas–solids distributor). Detailed description of this gas–solids distributor can be seen elsewhere [21]. These profiles show a fairly uniform distribution in the center region at $0 < r/R < 0.85$–0.9 and a high density peak at $r/R = 0.95$–0.975 near the wall, and the maximum is 2–3 times of the cross-sectional averaged solids fraction. The characteristics of radial solids profiles that there exists uniform center and near wall dense ring remains unchanged over a long axial distance of the downer from 1.2 to 4.2 m. These results are quite similar with those obtained in downers with smaller diameter by most of former researches such as Herbert et al. [9], Yang et al. [10], Wang et al. [11], Bai et al. [12], Wei et al. [13] and Lehner and Wirth [14,15]. Such special shape of radial solids fraction profile that a densification ring existing near the wall in the downer is not only observed through experiments conducted in different scale reactors, but also obtained by numeric simulations. Yang et al. [22] developed a two-dimensional two-phase turbulent model for flow of gas particles, and Cheng et al. [23] brought out a model based on kinetic theory, to simulate the hydrodynamic behaviors including radial solids distribution in the downer reactor. Both of them obtained the near wall densification phenomenon in radial solids fraction profiles.

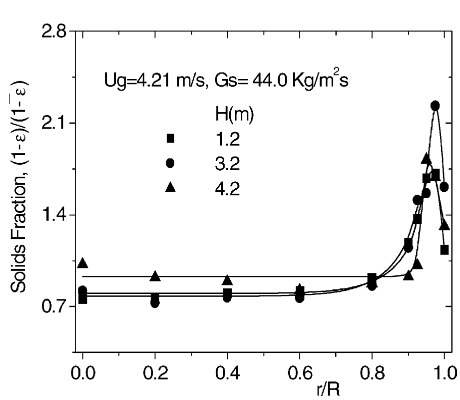

Fig. 3. Typical radial solids fraction profiles in different axial positions of the downer.

The forming mechanism of the near wall dense ring in the downer could be explained by some theory on gas–solids flow system, which was originally summarized by Kimm et al. [24]. In the center region where gas velocity is relatively high, the drag force acting on the particles is larger. This makes the particles tend to move away from the center region to the wall region in order to consume less energy [11]. The movement trend of particles away from wall to center in the downer can be explained using the kinetic theory of granular solids. As particles are much denser than gas, particles play the important role in describing the momentum transport for the gas–solids flow [25]. In the downer, gas and solids are co-currently down-flow along the direction of gravity, particles tend to be in a dispersed state and move independently [26]. The vertical moving particles in a dispersed state will pick up a random velocity and get the kinetic energy in the horizontal direction by the shear work imposed by the wall and the particle velocity gradient [25]. Due to the presence of the wall, the random velocities can only generate movement away from the wall. As the result of these two adverse trends, an annular densification is formed in some distance from the wall.

From the experiment results observed in this work together with former studies, the numeric simulation results and the gas–solids flow mechanism, the near wall dense ring could be clearly characterized in the downer reactor. Hence, it can be concluded that the solids uniformly distributed in the center region and a relatively annular dense region existing near wall is the unique characteristic of radial solids profile in the downer.

3.2. Radial solids fraction profiles of downer under different operation conditions

Radial solids fraction profiles at the axial position of 4.2 m below the gas distributor were obtained under different operating conditions, as shown in Figs. 4 and 5. The overall shape of radial solids fraction distribution does not change with the variety of superficial gas velocity U_g and the solids circulating rate G_s. The peak value of solids fraction and its radial position exhibit a little discrimination under different conditions, but there exist the near wall dense ring under all these operating conditions that U_g and G_s range from 2.27 to 9.45 m/s and 20 to 157 kg/m^2 s, respectively. The peak

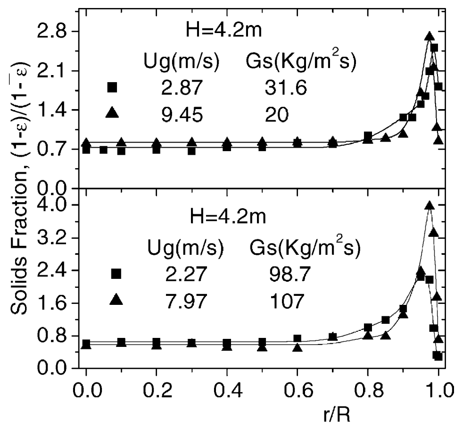

Fig. 4. Radial solids fraction profiles in operating conditions with different U_g.

value of solids fraction of the near wall dense ring is 2–4 times of the cross-sectional average solids fraction and its radial position is at $r/R = 0.95$–0.98 under the examined operating conditions. The shape of the radial solids fraction distribution remains relatively unchanged over such a wide operating condition. The forming mechanism of the near wall dense ring in the downer, which is related with the horizontal particle velocities converted from the kinetic energy in vertical direction by the shear force of the wall, can be used to explain such experiment results. Suppose solids circulating rate G_s is constant and superficial gas velocity U_g is increased. Then the near wall particles will obtain more energy, and the vertical kinetic energy will also be increased. So the particles will obtain more energy to have chance to move farther from the wall, but the increasing of U_g will also enlarge the drag force of the gas in central region and make the central particles move towards the wall. These two counter trends result in the little change of the peak value of solids fraction and its radial position in radial solids fraction profiles of the downer, as shown in Fig. 4. The increasing of solids circulating rate G_s will also cause similar two adverse trends that there are more particles that can get the chance to move towards the center by the wall shear and more particles that are moving towards the wall by the drag force imposed by the gas in the center. Such adverse trends also result in slightly alternation of overall shape of radial solids fraction profiles in the downer, as shown in Fig. 5. The results obtained in a downer with 150 mm diameter by Lehner and Wirth [14] show a little difference. They believe that for a constant superficial gas velocity the solids flow rate is of small importance for the radial solids fraction distribution and increasing gas velocity makes the peak move towards the center of the downer. Such discrimination is mainly due to the difference in the diameter of the downer. In their results, the maximum of solids concentration is at $r/R = 0.9$ for the superficial gas velocity $u_L = 1.25$ and 2.5 m/s, and at about $r/R = 0.85$ for $u_L = 3.8$ and 5 m/s. The absolute distance for the move of the peak position of the solids fraction is about 3.75 mm (for the diameter of downer is 150 mm). Such value is not remarkable for a large unit such as 418 mm in diameter in this work (just about 0.02 for relative distance r/R). The change in small-scale downer is relatively remarkable, but to a large-scale reactor in this work, such change is slight.

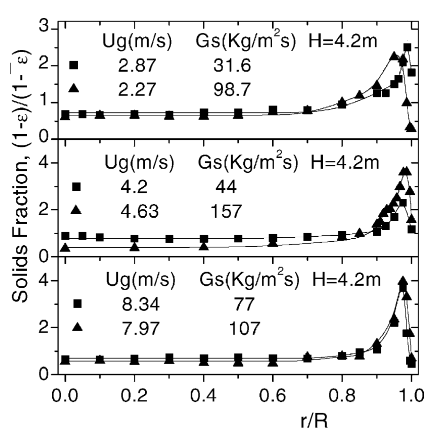

Fig. 5. Radial solids fraction profiles in operating conditions with different G_s.

3.3. Comparison of the radial solids fraction profiles in different scale downer

Radial solids profiles in different scale downers are compared in Fig. 6. They all exhibit a flat core region and a dense ring near wall, which means that the change of diameter does not alternate the overall shape of radial solids distributions in the downer. But the range of the flat core region is quite different from each other: for the 50 mm diameter downer, the solids uniformly distributed from $r/R = 0$ to 0.5, for the 140 and 150 mm downer, the flat core region existing at $r/R = 0$–0.75, and in the 418 mm ID downer of this work, the center region extending to approximate $r/R = 0.9$. Meanwhile, the peak position of the radial solids distribution is nearer to the wall when the diameter of downer increases and the proportion of the non-uniformly distributed region near wall to the whole diameter decrease.

The absolute radial distance from the position of the peak value to the wall in different scale downers are listed in Table 1. Although the relative radial distance from the peak position of dense ring to the wall varies in downers with different diameter, the absolute radial distance is a relative

Table 1
Comparison of radial distance from peak position of radial solids fraction profiles to the wall in different scale downer

Author	Diameter of downer (mm)	D (mm)
This work	418	5.2
Lehner and Wirth [14]	150	7.5
Wei et al. [13]	140	5
Wang et al. [11]	140	5
Herbert et al. [9]	50	10

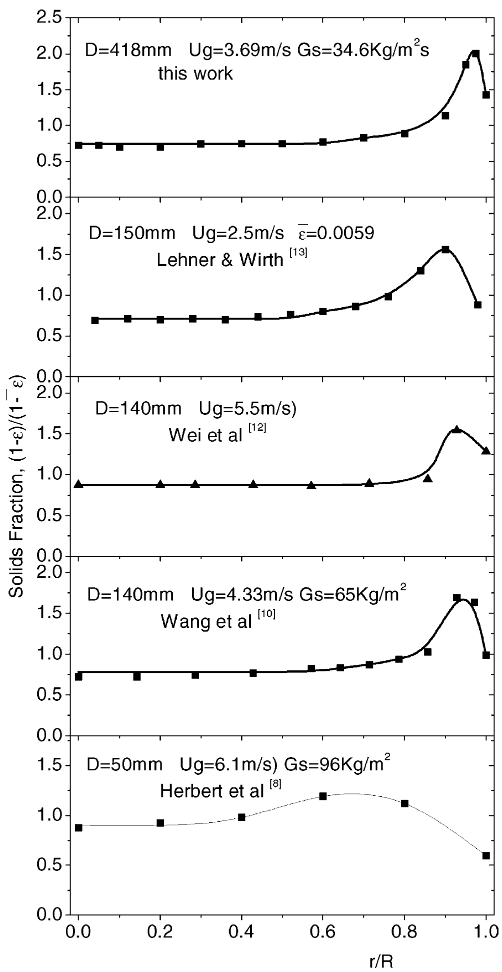

Fig. 6. Comparison of radial solids density distribution in downers with different diameter.

constant value. The magnitude of this absolute distance is about several millimeters and remains relatively unchanged in different scale downer. These experiment results also indicate that the wall of downer has significant influence on the radial solids distribution, and the forming of near wall dense ring is closely related with the wall effect. The effect caused by the wall on the radial solids distribution in the downer is not related with the dimensionless distance r/R, but the absolute distance r, for the effective range of the wall effect is a relatively constant value, which is very important to understand the scale-up feature of the downer.

3.4. Wall effect on the radial profiles of solids fraction in the downer

The wall structure at two different axial positions, 1.5 and 1.8 m below the entrance of downer, were modified to study the wall effect on the radial profiles of solids fraction in the downer. Fig. 7 shows the modification that the wall of downer was moved to the center for 10 mm, which means the radius of the downer diminishes 10 mm. The radial profiles of local solids fraction in these two types of wall structures under two operating conditions are shown in Fig. 8. The modification of the wall structure does not affect the overall distribution shape of local solids fraction in the downer, and the distributions also show a uniform core region and a dense ring near the wall. When the wall of the downer was moved to the center for 10 mm, the dense ring also moves to the center for about 10 mm. This phenomenon again indicates that the existence of near wall dense ring in the downer is closely related with the wall effect. As shown in Fig. 8, in the original wall, the maximum of solids fraction exists at about $r = 197$ mm (from center of the downer), and the

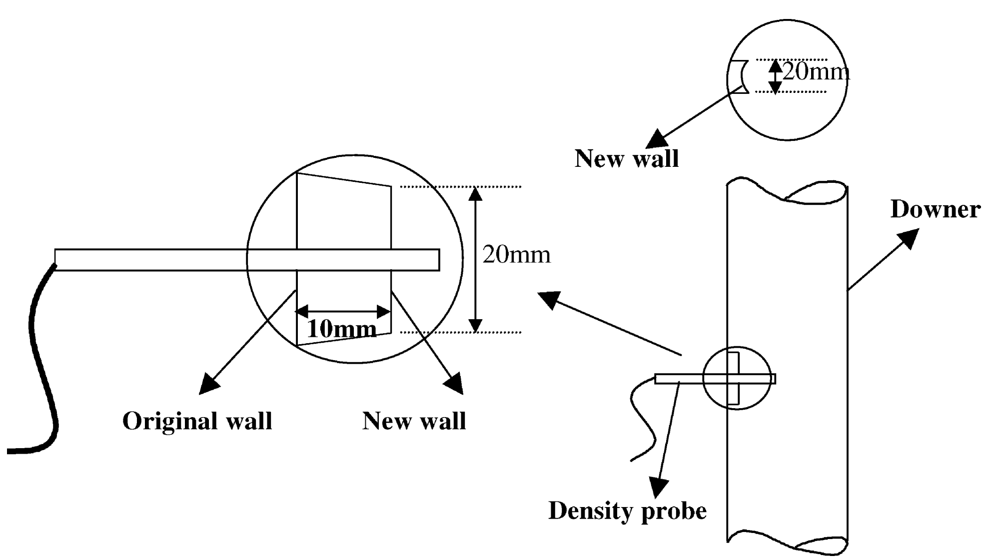

Fig. 7. Modification of the wall of the downer.

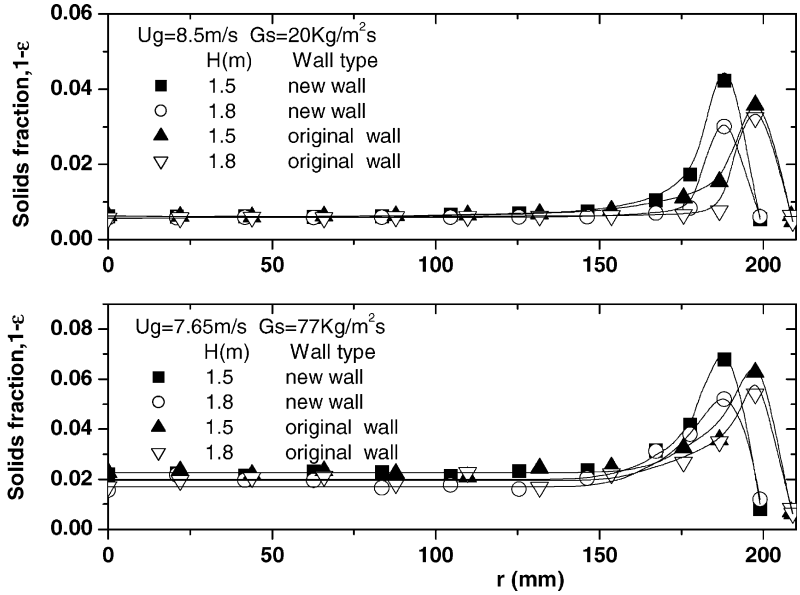

Fig. 8. Solids fraction distribution in the downer with different wall types.

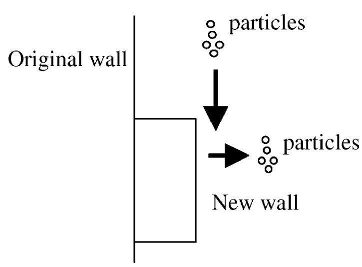

Fig. 9. Schematic diagram of particle movement in the near wall region in the modified wall structure.

distance from the new wall to the center of the downer is 199 mm. Then the solids at the position of $r = 197$ mm will go down directly to the position with 2 mm distance from the new wall. Thus the solids concentration at the position $r = 197$ mm will be relatively high in the experiment with new wall, but from Fig. 8, it can be seen that the solids at this position is very low. So we can conclude that it is the existence of the new wall that makes the solids move towards the center for about several millimeters and get the maximum of solids concentration at about $r = 187$ mm, as indicated in Fig. 9. The forming mechanism of the near wall dense ring is related with the collision between the particle and the wall [24], thus the distance from the dense ring and the wall should be a relatively constant value, which are quite coincident with the above experiment results.

4. Conclusion

Radial distribution of solids fraction in the 418 mm ID downer is fairly uniform in center and a relatively dense ring exists near the wall, which is similar with that in small-scale downer. The near wall dense ring is a unique character of the downer reactor and exists under all the operating conditions examined in this work. The peak value of the dense ring is about 2–4 times of the cross-sectional averaged solids fraction and the distance from its radial position to the wall is a relatively constant value that is about several millimeters. These two parameters change little with the alternation of operating condition and diameter of downer. The proportion of the area of the uniformly distributed center region to the whole cross-sectional area increases with the scale-up of the downer reactor. The existence of the near wall dense ring is closely related with the wall effect, and its forming mechanism can be explained by the kinetic theory of granular solids flow and the energy consumption analysis of the gas–solids flow system. The experiment results of this work help to understand the radial distribution of solids fraction in large-scale downer reactors and the scale-up feature of this excellent gas–solids reactor.

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