

Article

LDV measurements of particle velocity distribution in an annular stripper☆

Yongzheng Li¹, Xiaolai Zhang², Guangwei Zhai³, Haitao Zhang¹, Tao Li^{1,*}, Qiwen Sun³, Weiyong Ying¹¹ Engineering Research Center of Large Scale Reactor Engineering and Technology, Ministry of Education, State Key Laboratory of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China² School of Chemistry and Chemical Engineering, Shandong University, Jinan 250100, China³ State Key Laboratory of Coal Liquefaction and Coal Chemical Technology, Shanghai 201203, China

ARTICLE INFO

Article history:

Received 26 September 2018

Received in revised form 12 March 2019

Accepted 12 March 2019

Available online 4 April 2019

Keywords:

Annular stripper

Flow

Hydrodynamics

Particle velocity

Laser Doppler velocimeter

ABSTRACT

Particle descent velocities in an annular stripper were measured by a laser Doppler velocimetry (LDV) system. In the radial direction, particle descent velocity was relatively constant in the mid-region of the stripper and increased towards the walls on both sides, exhibiting an anti-U-shaped distribution. Particle descent velocity in the radial mid-region increased with the increase of superficial gas velocity, and the maximum in the outer wall region increased significantly with the increase of solid mass flux. Superficial stripping gas velocity had stronger effect on particle velocity distributions near the stripper gas distributor, and such effect weakened with the increase of the distance from the distributor. Local particle velocity and its radial profiles could be adjusted by changing the superficial stripping gas velocity. Empirical formulas were established to describe the relationships between the local particle velocity and cross-sectional averaged velocity based on the effects of operating conditions and measuring positions. The result showed that the predicted data was in good agreement with the experimental value.

© 2019 The Chemical Industry and Engineering Society of China, and Chemical Industry Press Co., Ltd.

All rights reserved.

1. Introduction

In a free vertical movement, particles and gas usually move either in an upward or downward direction when there is no distribution plate in the reactor. Therefore, the gas–solid two-phase flow in the pipelines has three different conditions [1]: particles move upward with gas (such as a riser), gas–solid phases flow co-currently downward (such as a downer), and gas travels upward while solid travels downward (such as a stripper). In the past decades, many hydrodynamics researches [2–6] about riser and downer have been carried out due to their wide use in commercial applications, but the investigation on complex gas–solid counter-current movement in the stripper was relatively deficient.

When particles transfer from a fluidized bed into another one through standpipe, the interstitial hydrocarbon gases move into another fluidized bed with the particles. If particles are porous solids, the entrained gas in holes should be replaced by the stripping gas [1]. For example, in FCC units, catalysts require continuous regeneration due to rapid deactivation. Hydrocarbons, which present in the interstitial gas, and adsorb on the catalyst surface [7], should be stripped before

catalysts enter regenerator. During the downward movement of solid catalysts along the tripper, the countercurrent steam strips the interstitial gases from the surface or holes of the particles [8]. High efficiency stripper not only enhances the yield of light oil, but also reduces the steam consumption and the load of the regenerator, which is important for saving energy and maintaining heat balance of the units. However, for a commercial stripper, flooding and bridging can happen as undesired phenomena. These operating problems impede solid circulation, reduce gas–solid contact efficiency, and may even stop the particle circulation and then interrupt the process [8]. Therefore, proper understanding of the hydrodynamics in strippers is essential in order to choose the appropriate operating parameters and optimize the design process.

The hydrodynamics and stripping characteristics have been found to depend strongly on superficial gas velocity and solid mass flux [9–14]. Concentration and velocity profiles of gas–particle two-phases were unevenly distributed in the stripper [15]. Moreover, the shape and position of internal components greatly influenced the solids holdup profiles of the stripper [16] and appropriate baffles intensified the gas–solid contact and efficiently improved the stripping efficiency [11,17,18]. Various configurations for strippers have been studied [19–21]. Zhang *et al.* [22] found that a two segment annular stripper had higher stripping efficiency than an empty cylinder stripper and disk-donut stripper under the same operation condition. Cui *et al.* [23] studied the effects of stripping steam injection on stripping efficiency and explored the steam

☆ Supported by the National High-Tech R&D Program of China (2011AA05A204) and the Fundamental Research Funds for the Central Universities (222201817013).

* Corresponding author.

E-mail address: tti@ecust.edu.cn (T. Li).

injection configurations. Li *et al.* [24] proposed a new stripping process, which significantly reduced the energy consumption and simplified the overhead vapor route.

However, among these various investigations about different inlet structures and internals of stripper, few studies were conducted on particle velocity distribution in strippers. Particle velocity and its distribution of the gas–solid flow are important hydrodynamic characteristics, which affect the heat and mass transfer, contacting efficiency, and catalyst residence time distribution. It is very important for appropriate industrial design, accurate operation, successful scale-up and process modification to fully understand the particle flow structure in stripper.

In this study, laser Doppler velocimeter (LDV) measurement technique was used to research the particle velocity characteristic in a large scale annular stripper. Without probe inserted into the fluid, this technique does not interfere with the flow pattern [25]. The effects of superficial gas velocity, solid mass flux, and superficial stripping gas velocity on particle velocity were discussed. The purpose of this paper is to deepen the understanding of particle velocity distribution in the stripper and provide useful data for the design and operation of the stripper.

2. Experimental

2.1. Experimental setup

Experiments were conducted in a Plexiglas circulating fluidized bed (CFB) (see Fig. 1), which consists of riser, stripper, catalyst regenerator, precipitator and feed tank. The stripper was an annular device coaxial to the riser. The riser was 4.8 m long and 0.15 m i.d., and the

stripper was 1.4 m long and 0.43 m i.d. A branched pipe distributor (see Fig. 2(a)) with 92 nozzles was equipped at an altitude of 0.2 m in the riser. To make the gas distribution more uniform, a perforated plate (see Fig. 2(b)) with 208 holes of 0.002 m in diameter was installed above the gas distributor.

Glass beads with a mean diameter of 89 μm , 2410 $\text{kg}\cdot\text{m}^{-3}$ particle density and 1521 $\text{kg}\cdot\text{m}^{-3}$ bulk density were used as fluidized solids. After being measured by a glass rotameter, the treated compressed air (water, oil, and impurities were removed) was fed into the branched pipe gas distributor. Initially, the solid particles were piled up at the bottom of the stripper. When the valves 9 and 10 were opened, solids traveled into the riser reactor above the perforated plate. Due to gas–solid drag, the particles moved upward along the riser with the fluidized gas. At the top of the riser, most of the particles bounced back into the stripper after hitting the hat shaped structure and passed through the stripper from top to bottom. A ring type distributor (see Fig. 2(c)) with 34 nozzles was installed at the bottom of the stripper ($H = 2.65$ m). In the annular stripper, stripping gas traveled upward, which was contrary to the motion of the particles. Solid particles passed through the stripping section and returned to the CFB riser via a circulating pipe of 0.08 m in diameter. Solid mass flux was adjusted with ball valves installed on the circulating pipe. During the experiment, only a very small amount of particles following with the gas left the reactor and entered a bag filter whose aim was for gas–solid separation. The separated particles were returned periodically to the fluidize bed system. Since this paper only aimed to study the particle velocity characteristic in the stripper, valves 12 and 14 were closed because the particles did not need to enter the catalyst regeneration system.

2.2. Particle velocity measuring system

LDV offers an accurate and applicable method to research particle velocities in a sufficiently dilute fluidization system [26–30]. In this study, particle velocity in an annular stripper was investigated by using a TSI LDV system. An illustration of the LDV system is provided in Fig. 3, which mainly included laser, multicolor beam separator, transmitting/receiving optics, photo detector module, signal processor, and data analysis system. A 5 W argon-ion laser was employed in LDV to produce a coherent beam that illuminated a particle moving in the flow field. And this particle produced a Doppler shift which was proportional to its velocity. Then, particle velocity was calculated using Doppler frequency, laser wavelength, and the angle between beams. The detailed measurement principle has been mentioned in previous published articles [27,31,32]. Unfortunately, this technique can only be used in the low solids fraction. In order to determine the available range of LDV, local solids holdups were obtained with the fiber-optic concentration probe at each axial height. As shown in Fig. 4, the solids holdups were higher in both wall (inner wall and outer wall) regions of the annular stripper, and the maximum of local solids holdup was about 0.016, which was higher than the solids holdup obtained under experimental conditions. Thus, the solids holdup in the stripper was low enough to guarantee the accuracy of the LDV system. In addition, the accuracy of particle velocity could be determined by data rate, and higher data rate collected can obtain more stable and accurate measurement data. In our study, the data rate was large enough and the sampling time was typically over 60 s or the number of sampled particle reached 20000 at each measurement position, which was enough to ensure the accuracy of the measurement data.

2.3. Experimental scheme

In the experiments, various operating conditions were considered. The superficial gas velocity (based on cross-sectional area of riser), U_g , mean solid mass flux (based on cross-sectional area of riser), G_s , and stripping gas velocity (based on cross-sectional area of stripper), U_g' , were 1.57–2.20 $\text{m}\cdot\text{s}^{-1}$, 4.42–12.61 $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and 0.000–

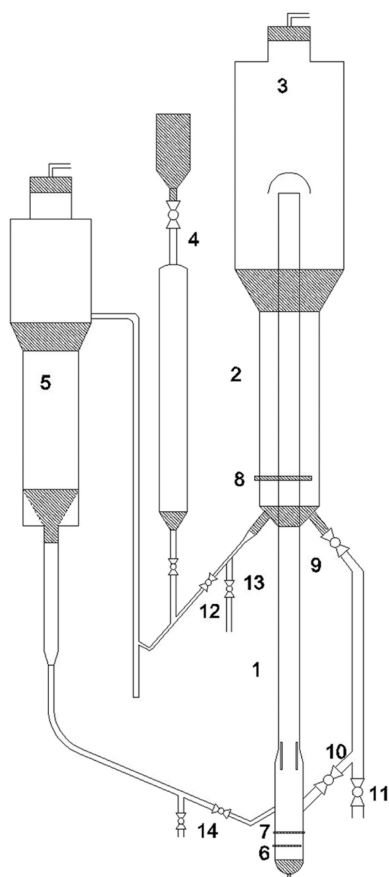


Fig. 1. Schematic diagram of large-scale cold model experimental apparatus. 1. Riser; 2. Stripper; 3. Precipitator; 4. Feed tank; 5. Catalyst regenerator; 6. Branched pipe distributor; 7. Perforated plate; 8. Stripper gas distributor; 9–14. Ball valve.

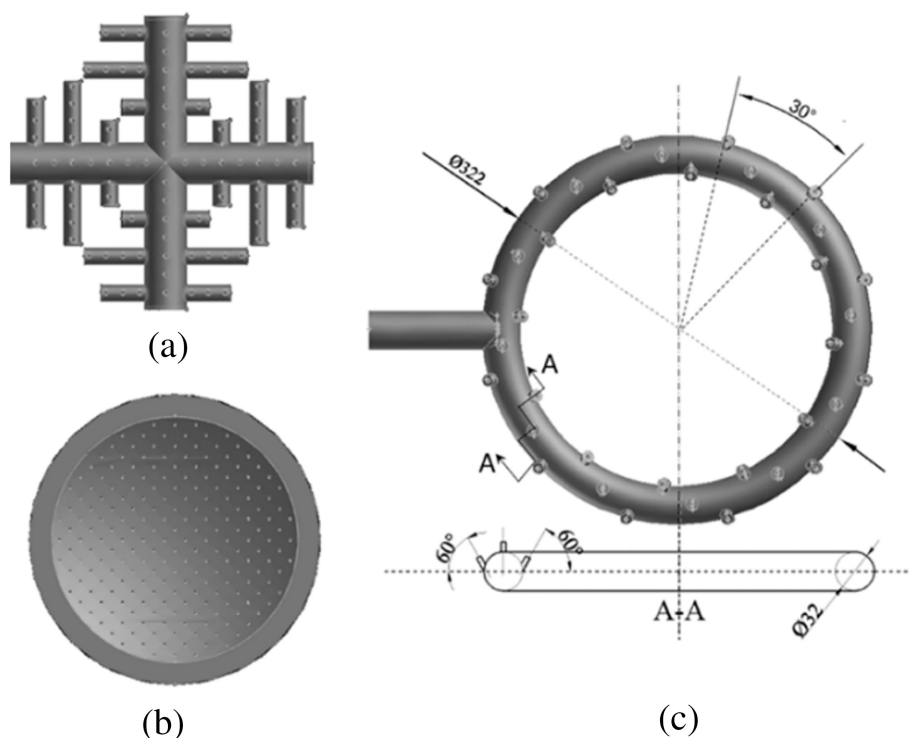


Fig. 2. (a) Branched pipe distributor; (b) perforated plate; (c) stripping gas distributor.

$0.088 \text{ m} \cdot \text{s}^{-1}$, respectively. H represents the distance from the measured levels to the perforated plate. The local particle velocity in the stripper was measured at 12 radial positions ($r/R = 0.42, 0.47, 0.51, 0.56, 0.60, 0.65, 0.70, 0.74, 0.79, 0.84, 0.88, 0.93$) on 6 axial levels ($H = 2.72, 2.82, 2.92, 3.02, 3.12, 3.22 \text{ m}$). The top view of the annular stripper and the radial measuring positions (filled circles) are showed in Fig. 5(a). In order to eliminate the random error and ensure the precision and reliability of the measured data, the measurement of each point was repeated several times. In addition, the local particle velocities were measured on six different radial measuring paths around the

circumference of the annular stripper (as shown in Fig. 5(a)) to investigate the influence of different measuring directions on the measurement results. The angle between the two adjacent paths was 60° . Fig. 5(b) shows the local particle velocities on six different measuring paths when $U_g = 2.20 \text{ m} \cdot \text{s}^{-1}$, $G_s = 4.42 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, $U_g' = 0.000 \text{ m} \cdot \text{s}^{-1}$, and $H = 2.92 \text{ m}$. After the gas–solid two-phase in the annular stripper reached steady fluidization state, there was no significant difference in the measured values of local particle velocity along each path. Wang *et al.* [33] have also uncovered a similar phenomenon: the standard deviations among measurements (at the same radial position)

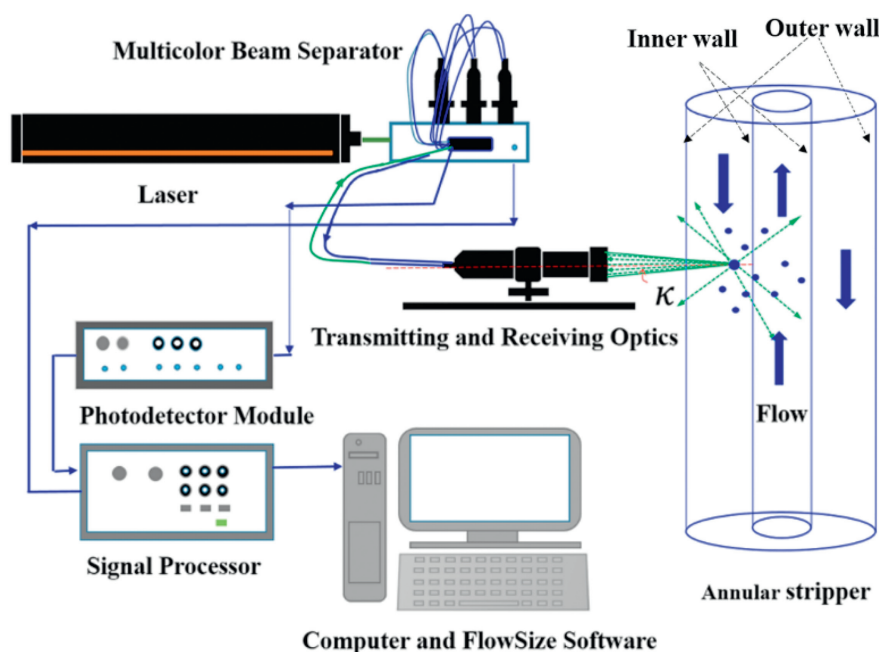


Fig. 3. Schematic diagram of laser Doppler velocimeter.

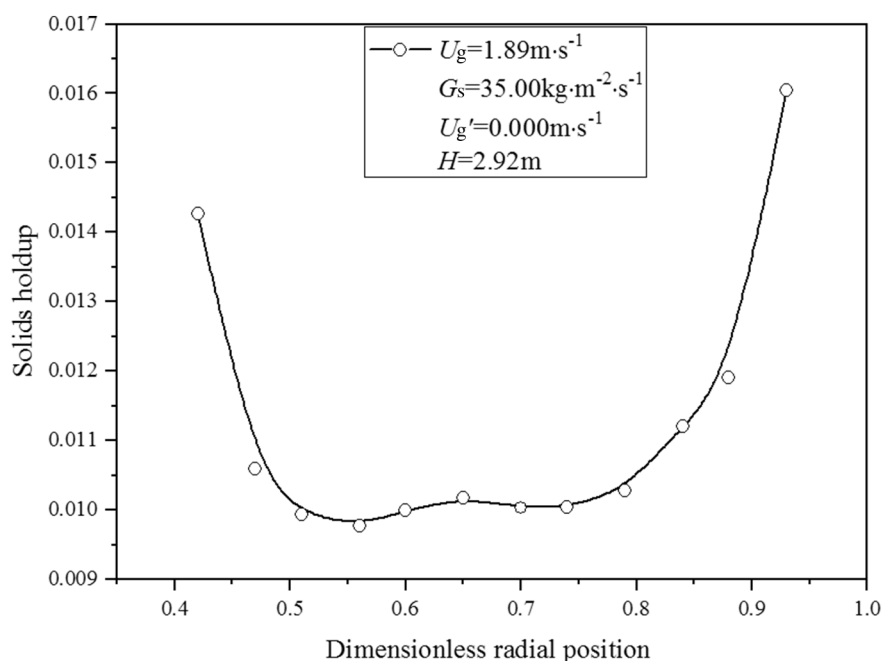


Fig. 4. Radial profile of solids holdup in the annular stripper.

in different directions were less than 0.15%. Therefore, radial symmetry was assumed in this paper and all particle velocities were obtained along one of the measuring paths (green filled circles in Fig. 5(a)). In addition, some relevant solids holdups were measured at different operating conditions with the fiber-optic concentration probe to better explain the particle velocity distribution.

3. Results and Discussion

3.1. Radial profiles of particle velocity in large scale stripper

Fig. 6 provides the radial distributions of particle velocity at 6 axial levels. The superficial gas velocity, solid mass flux, and stripping gas

velocity were $1.57 \text{ m} \cdot \text{s}^{-1}$, $4.42 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and $0.044 \text{ m} \cdot \text{s}^{-1}$, respectively. Overall, the particle velocity profiles were non-uniform along radial direction. All the particle velocities were less than zero, which meant the direction of movement of the particles was the same as the direction of the gravity. It should be noted that smaller values denoted larger particle descent velocities.

As shown in Fig. 6, radial profiles of particle velocity on each level (except for $H = 2.72 \text{ m}$) exhibited a relatively stable mid-region ($r/R = 0.56 - r/R = 0.84$), and then gradually decreased towards the inner wall and outer wall, which was contrary to the radial distribution trend of solids holdup. According to this study (e.g. Fig. 4) and previous research [6,34–37], particles tended to accumulate and form a dense annulus near the wall. By comparison, the radial position of the

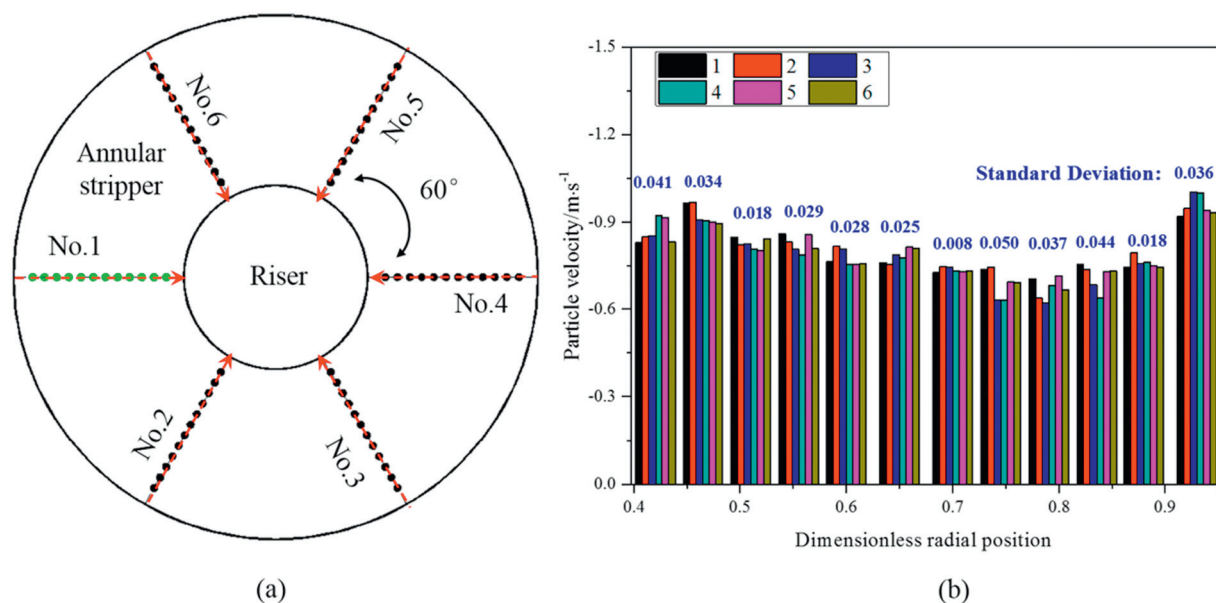


Fig. 5. The top view of the annular stripper (including radial measuring positions and measuring paths) and the effect of measuring path on local particle velocity.

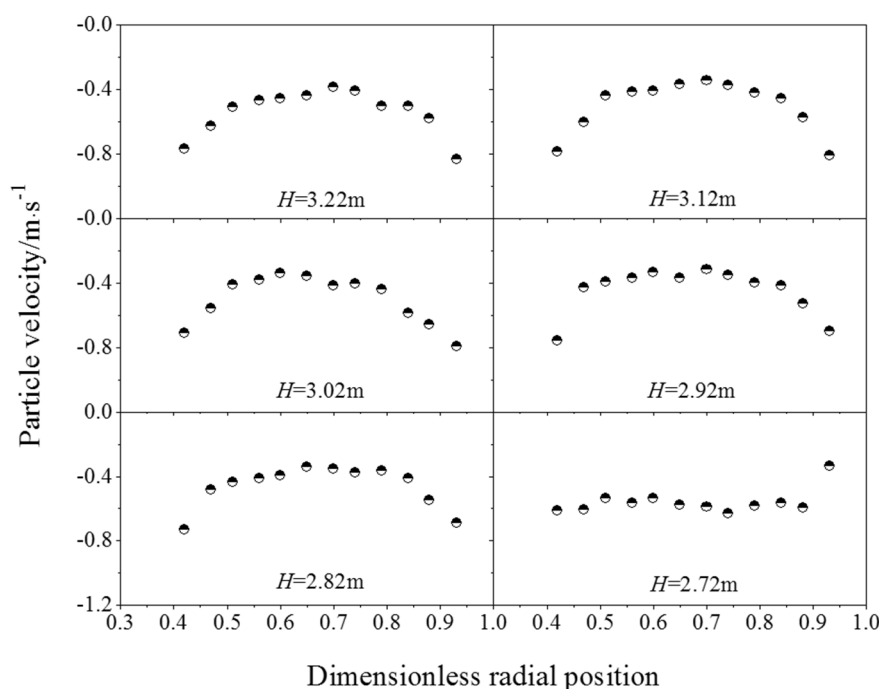


Fig. 6. Radial profiles of particle velocity in the large scale stripper ($U_g = 1.57 \text{ m} \cdot \text{s}^{-1}$, $G_s = 4.42 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, $U_g' = 0.044 \text{ m} \cdot \text{s}^{-1}$).

maximum particle descent velocity ($r/R = 0.42$ or $r/R = 0.93$) was almost consistent with that of the maximum solids holdup.

In fact, particle descent velocity was greater than gas descent velocity within the measurement range ($H = 2.72 \text{ m}$ – $H = 3.22 \text{ m}$) of the current experiments. In the process of particle falling, gravity was the dominant force, while the gas–solid drag force became the resistance. Therefore, the formation reason of the radial particle velocity distribution could be explained as follows: in the wall region on both sides of the stripper, the solids holdup was higher, forming two relatively denser annular layers, which may be related to the wall effect and/or the special hat shaped structure on the top of the riser. A large number of particles rebounded back into the stripper with certain angles and moved downward along the inner and outer walls. The outer particles of the dense annulus had shielding effect on the gas–solid drag force, causing a decrease of upward force applied to the inner particles [28]. Therefore, the total upward drag force on particles in this region was reduced, causing a higher slip velocity and a larger descent velocity [6]. Meanwhile, the number of particles in the radial mid-region was relatively small due to the particle aggregation in the wall region. According to the energy-minimization multi-scale (EMMS) model [38,39], stripping gas was more inclined to move upward in the mid-region of the stripper with minimal resistance rather than through the dense phase in the wall region. In addition, the shielding effect of outer particles in the mid-region became weaker, so the particles encountered greater upward resistance in the process of falling. It was evident that clustered particles moved downward faster than the dispersed particles. Therefore, the particle descent velocities exhibited an anti-U-shaped distribution along the radial direction of the stripper.

The axial development of particle velocity radial profiles was also displayed in Fig. 6. There was no obvious development trend in the radial profile shape along the gas–solid flow direction from $H = 3.22$ to $H = 2.82 \text{ m}$, which was probably because the axial measurement range was too narrow to observe the whole axial development process of particle velocities. Another reason was that particle velocity might have been fully developed. The variation in particle velocity along the direction of motion could be neglected, which meant acceleration force (gravity) and deceleration force (air drag force and wall friction)

on particles were in equilibrium. However, at the bottom of the stripper ($H = 2.72 \text{ m}$), the radial profile became more uniform, which was attributable to the fact that particles in this region were closer to the stripping distributor and were strongly influenced by the stripping gas. The effects of stripping gas velocity on the radial profiles of particle velocity will be discussed in Section 3.4.

3.2. Effects of superficial gas velocity

Fig. 7(a) showed that the superficial gas velocity clearly affected the local particle velocity. Under the same solid mass flux and stripping gas velocity, increasing superficial gas velocity led to larger particle descent velocity at almost every radial position. It was probably because the particles, which were bounced into the stripper, got more energy both in the wall and mid-region to impel particles downward at higher superficial gas velocity.

In Fig. 7(a), with the increment of superficial gas velocity, the particle descent velocity increased obviously in the radial mid-region of the stripper, while small changes occurred in the wall region. To better describe this change, the Probability Density Functions (PDFs) distribution of particle velocity was examined, as shown in Fig. 7(b). In the wall regions on both sides of the stripper, with the increase of superficial gas velocity, the shape and peak value (the occurrence probability of the particle velocity was the largest) of the probability distribution curve of particle instantaneous velocity did not change much. In the radial mid-region, the PDFs curve and its peak value were shifted to the left, indicating that the particle descent velocity gradually increased as the superficial gas velocity increased.

In addition, particles in the dispersed state had an apparently random velocity in a direction perpendicular to the mean velocity gradient [40]. Therefore, the particles had a horizontal velocity during the falling process in the stripper. When the horizontal motion of particles collided with the wall, the particles rotated and moved away from the wall towards the mid-region. But in the meanwhile, particles in the radial mid-region were subjected to a greater drag force because of higher gas velocity, which caused the particles to move from the mid-region to the walls [36,41]. With the increase of superficial gas velocity, particles obtained more energy to move

away from the wall while the air drag force was increased and made more particles move towards the walls [36]. If these two opposing trends were in equilibrium, the solids holdup would remain relatively stable in the dense wall region. This phenomenon was confirmed by the variation of the radial profiles of solids holdup in Fig. 7(c) as a function of superficial gas velocity. As the superficial gas velocity increased, the solids holdup in wall regions on both sides of the stripper decreased slightly, so the particle descent velocity change in these regions was not obvious. In the radial mid-region of the stripper, as the superficial gas velocity increased, the solids holdup decreased significantly, but the effect of the superficial gas velocity (downward in stripper) on the downward particle was greater than that of the upward drag force. Finally, the particle descent velocity increased with superficial gas velocity.

3.3. Effects of solid mass flux

In addition to superficial gas velocity, solid mass flux is another important factor influencing the particle velocity profiles of the gas–solid system. Radial profiles of particle velocity under different solid mass flux were plotted in Fig. 8(a). Particle descent velocity in the outer wall region obviously increased with solid mass flux, but altered slightly in other regions of the stripper. This implied that the difference between the maximum and minimum velocities was greater under higher solid mass flux than that under the lower solid mass flux. As shown in Fig. 8(b), as the solid mass flux increased, the peak of the particle velocity probability density curve shifted significantly towards the left side of coordinate axis (representing the particle descent velocity increased) at the $r/R = 0.93$ position where the maximum particle descent velocity appeared. However, in the inner wall region and the radial mid-region, the peak value of the PDFs changed slightly to the right (representing the particle descent velocity decrease). This phenomenon could be explained by the radial profiles of solids holdup shown in Fig. 8(c): with the increase of solid mass flux, the cross-sectional averaged solids holdup increased, which made more particles move horizontally from the radial mid-region towards the wall under the action of gas drag force. At the same time, the wall effect was aggravated, and more particles in the outer wall region were moved towards the mid-region by the wall shear force [36]. However, particles from the wall region had low kinetic energy and had difficulty in entering into the mid-region where the energy was relatively high [42]. Therefore, under the combined effect of the two opposite trends, a large number of particles gathered in the region near the outer wall ($r/R = 0.93$) and eventually formed a dense ring. Besides, compared with dispersion in dilute phase, particles tended to aggregate in dense clusters [39]. As the solid mass flux increased, the solids holdup in the wall region became higher and the shielding effect of the outer particles enhanced. Therefore, particle descent velocity increased obviously in the dense annular region. In addition, particle descent velocity reduced weakly in the mid-region as the stripping gas tended to move upward from the radial mid-region.

3.4. Effects of stripping gas velocity

As shown in Fig. 6, the effect of stripping gas velocity on particle velocity radial profiles gradually decreased along the stripping gas flow direction. It was mainly because the effect on the particles in upper space was hindered by the gas–solid suspension segment. In the process of passing through the stripper from the bottom to the upper section, stripping gas was bound to lose energy. In the near wall region, suspended particle concentration was higher. Therefore, the energy loss was more serious than that in the mid-region because of the shielding effect of the outer particles during the stripping gas ascent process. Taking the radial profiles at $U_g' = 0.044 \text{ m} \cdot \text{s}^{-1}$ as an example, the particles in the upper levels were less affected by the stripping gas velocity and the overall radial profiles remained obviously non-uniform.

Fig. 9, which compared the radial profiles of particle velocity among different stripping gas velocities in the upper section of stripper, indicated that radial profiles were similar while the non-uniformity increased with stripping gas velocity. Particle descent velocity, especially in the radial mid-region, decreased obviously with increasing stripping gas velocity, which was mainly because the more stripping gas tended to move upward in the mid-region with minimal resistance. In addition, higher solids holdup near the wall made the particle velocity insensitive to the change of stripping gas velocity.

In Fig. 10, the effects of the stripping gas velocity on the radial profiles of particle velocity at $H = 2.72 \text{ m}$ were provided. With the increase of the stripping gas velocity, radial profiles became uniform and the maximum particle descent velocity disappeared under a fixed solid mass flux and superficial gas velocity. As the stripping gas velocity further increased, the U-shaped distribution arose possibly because of the special geometry of the stripping gas distributor (see Fig. 2(c)) at the bottom section. Moreover, under higher solid mass flux, larger stripping velocity was needed to make the maximum of particle descent velocity disappear.

Fig. 11 further showed the effects of superficial stripping gas velocity on particle velocity in the lower section of the stripper ($H = 2.82 \text{ m}$). Particle descent velocity always decreased with the increase of the stripping gas velocity, but this trend was particularly apparent in the wall regions on the both sides of the stripper, which was mainly because particle aggregation in these regions became difficult so that the dense annulus could not be formed due to the increase of superficial stripping gas velocity (as shown in Fig. 12). Eventually, the shielding effect of the outer particles on the drag force mentioned above was reduced or even disappeared.

Fig. 13 showed the effect of superficial stripping gas velocity on the instantaneous particle velocity distribution and its occurrence frequency at different radial positions. As the superficial stripping gas velocity increased, the probability density curves of the particle velocity moved to the right, which meant that the descent velocity of the particles at each local position was reduced. The specific performance was that the variation of particle velocity distribution curve in the radial middle area of the stripping section was weak, while that in the inner and outer wall regions changed significantly. Taking the PDFs of particle velocity at $r/R = 0.88$ and $r/R = 0.42$ as examples, not only the peak of PDFs curve shifted to the right obviously, but also the velocity distribution was more concentrated.

Fig. 10 also showed that when solid mass flux and stripping gas velocity were constant, particle descent velocities always increased with the increase of U_g . This is similar to the situation described previously in Section 3.2. Besides, the radial profiles of particle velocities became more uneven as the solid mass flux increased. Taking the radial profiles at $U_g' = 0.044 \text{ m} \cdot \text{s}^{-1}$ as an example, when solid mass flux went up to $12.61 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, the maximum descent velocity occurred at $r/R = 0.93$. When the stripping gas velocity was less than or equal to $0.044 \text{ m} \cdot \text{s}^{-1}$, the variation of particle velocity radial profiles with solid mass flux was similar to what has been discussed in Section 3.3. However, the particle descent velocities increased in all radial regions with increasing solid mass flux when stripping gas velocity was higher than $0.044 \text{ m} \cdot \text{s}^{-1}$. This could be ascribed to the cross-sectional averaged solids holdup increased with the enhancement of solid mass flux. The particles, which should have been clustered in the wall region, were more or less dispersed by upflow with the increase of stripping gas velocity because of the special structure of the stripper gas distributor and the increase of superficial stripping gas velocity. When stripping gas velocity went up to some extent, particles were difficult to aggregate in the wall region and tended to move to the radial mid-region and ultimately resulted in higher solids holdup (as shown in Fig. 12), so that particle descent velocity in this region increased with the increase of solid mass flux.

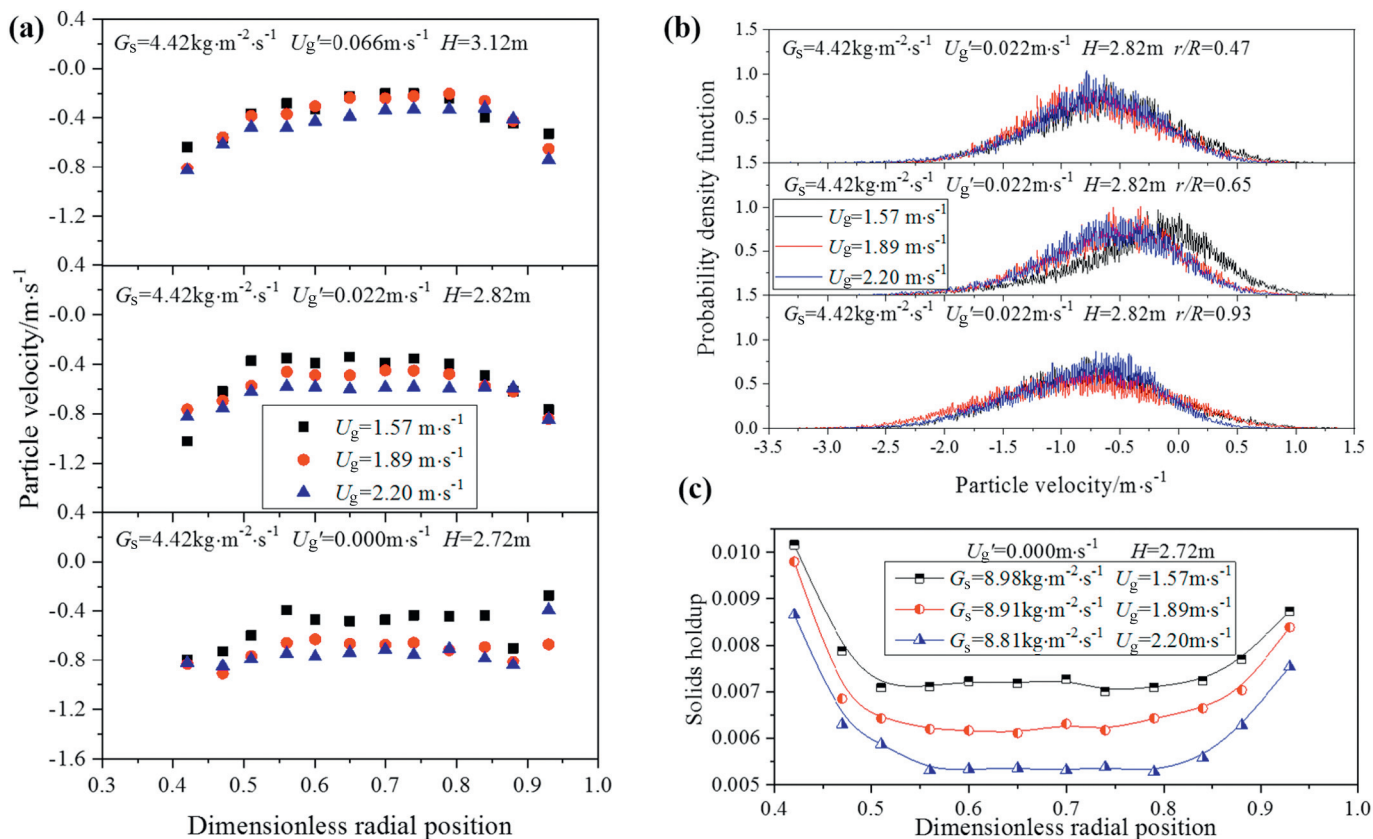


Fig. 7. Effect of superficial gas velocity on (a) radial profiles of particle velocity, and (b) probability density function of particle velocity, and (c) radial profiles of solids holdup.

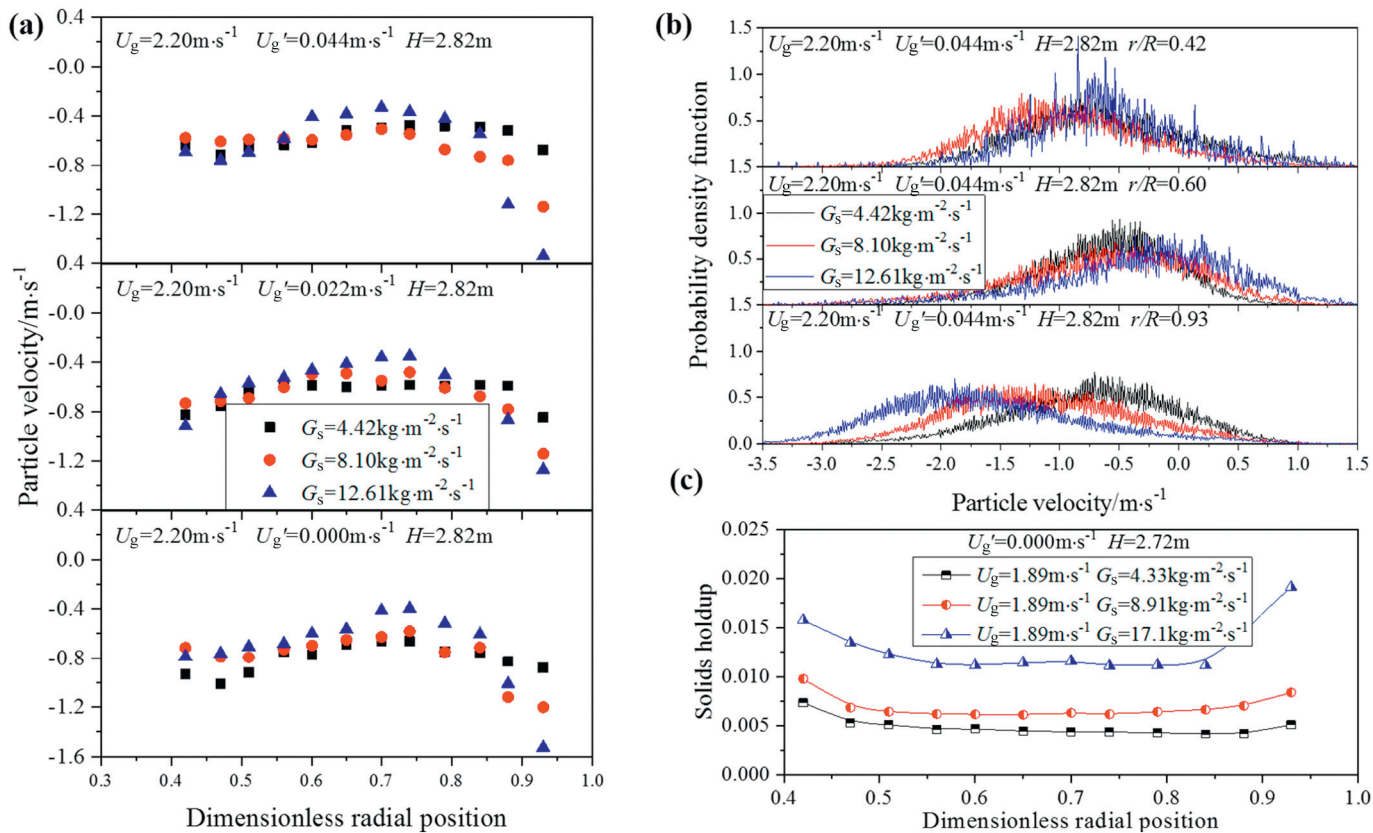


Fig. 8. Effect of solid mass flux on (a) radial profiles of particle velocity, and (b) probability density function of particle velocity, and (c) radial profiles of solids holdup.

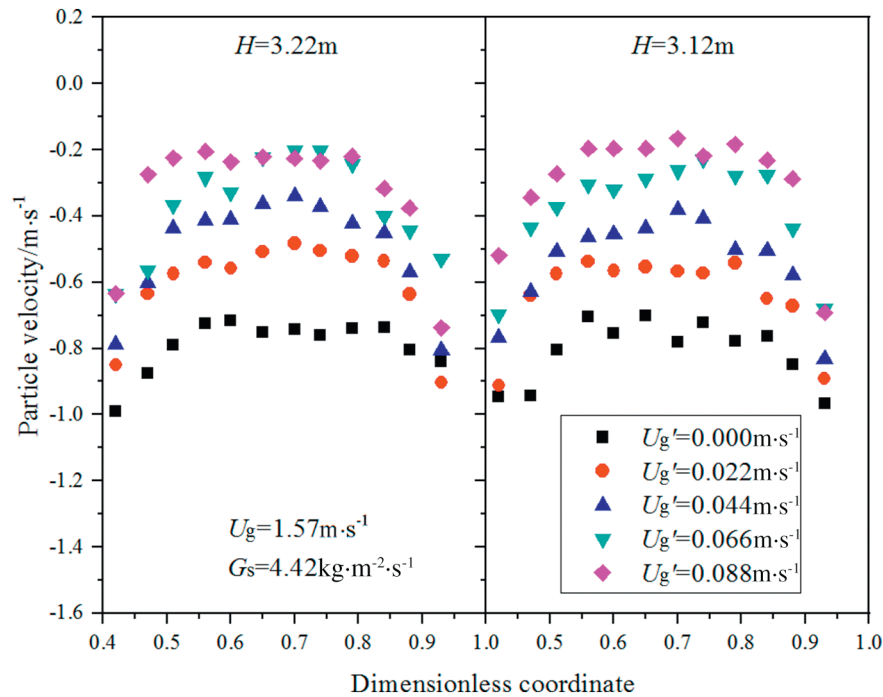


Fig. 9. Radial particle velocity profiles under different stripping gas velocities. ($U_g = 1.57 \text{ m} \cdot \text{s}^{-1}$, $G_s = 4.42 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$).

Therefore, the stripping gas velocity has a noticeable impact on the macro gas–solid flow. It is reasonable to expect that superficial stripping gas velocity can be used to adjust the residence time distribution of catalysts in the stripper of the industrial reactor according to the actual need.

3.5. A correlation for particle velocity in the upper section of stripper

The other purpose of this paper was to propose a suitable empirical formula for predicting the particle velocity in the annular stripper.

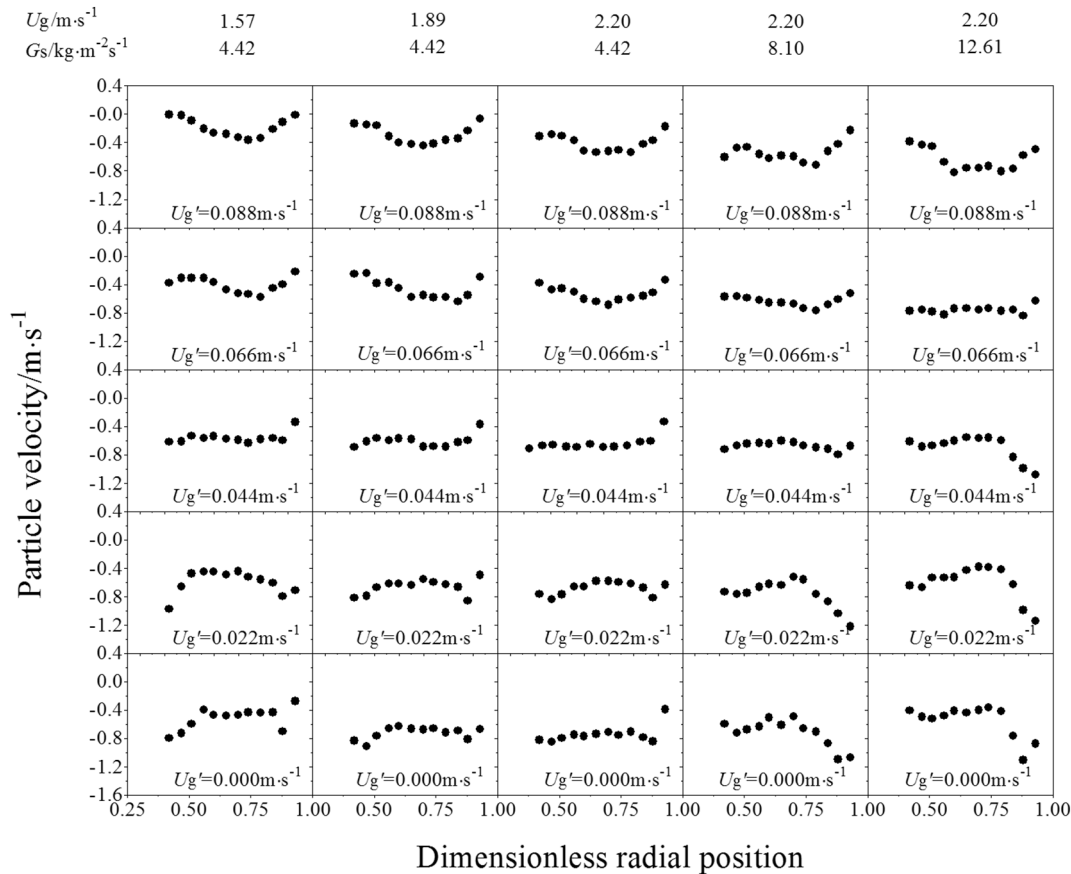


Fig. 10. Radial particle velocity profiles at the axial level of $H = 2.72 \text{ m}$.

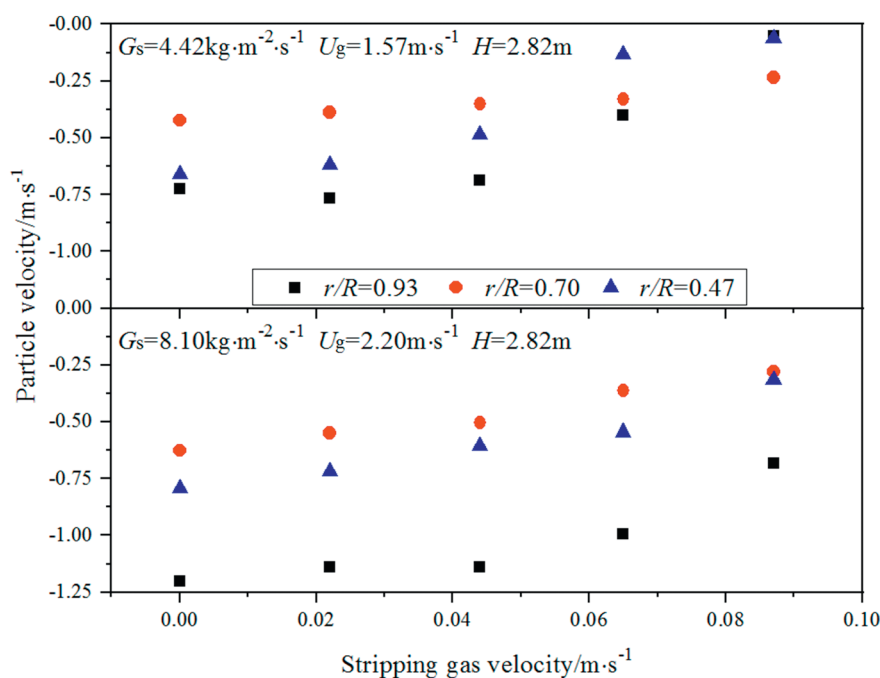


Fig. 11. Effects of stripping gas velocity on particle velocity at different radial positions.

From the experimental results in Figs. 6–11, we may conclude that the superficial gas velocity, solid mass flux, and stripping gas velocity jointly affect the radial profiles of particle velocity in the annular stripper. Therefore, particle velocity can be considered as a function of the particle/gas properties, stripper structure, measuring positions, and operation conditions, i.e.

$$V_p = f(d_p, \rho_p, U_g, G_s, \rho_g, \mu_g, U'_g, R, r) \quad (1)$$

To make the V_p term dimensionless, it was modified into the form as $\frac{V_p}{V_p}$. So Eq. (1) could be written as

$$\frac{V_p}{V_p} = a \left(\frac{r}{R} \right)^b \left(\frac{G_s}{\rho_p U_g} \right)^c (Fr_{d_p} + d)^e \quad (2)$$

Based on the variation of $\frac{V_p}{V_p}$ with r/R , the radial region for association was divided into three ranges as $0.42 \leq r/R \leq 0.56$, $0.56 < r/R \leq 0.74$, and

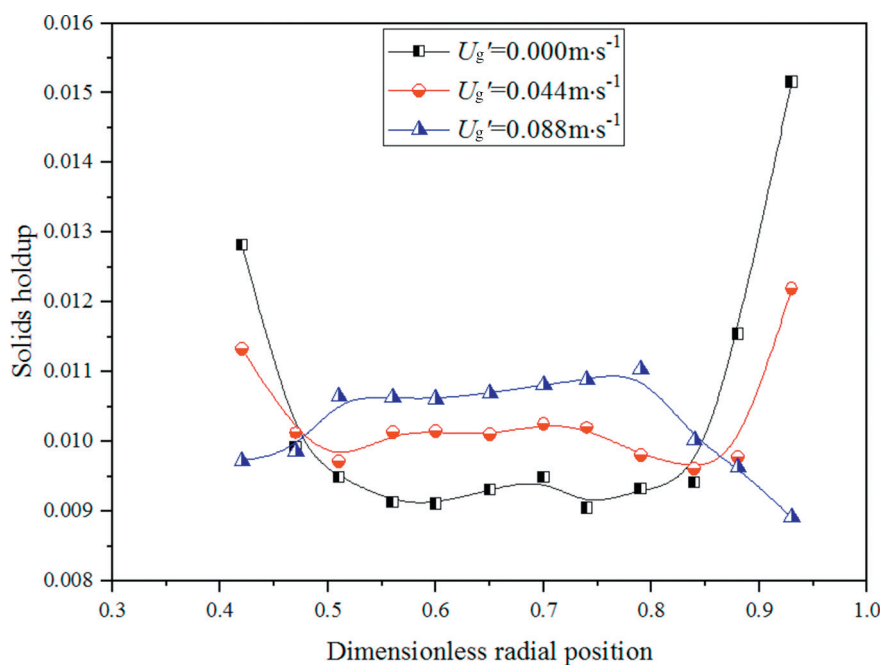


Fig. 12. Effects of stripping gas velocity on radial profiles of solids holdup. ($U_g = 1.89 \text{ m} \cdot \text{s}^{-1}$, $G_s = 16.8 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$).

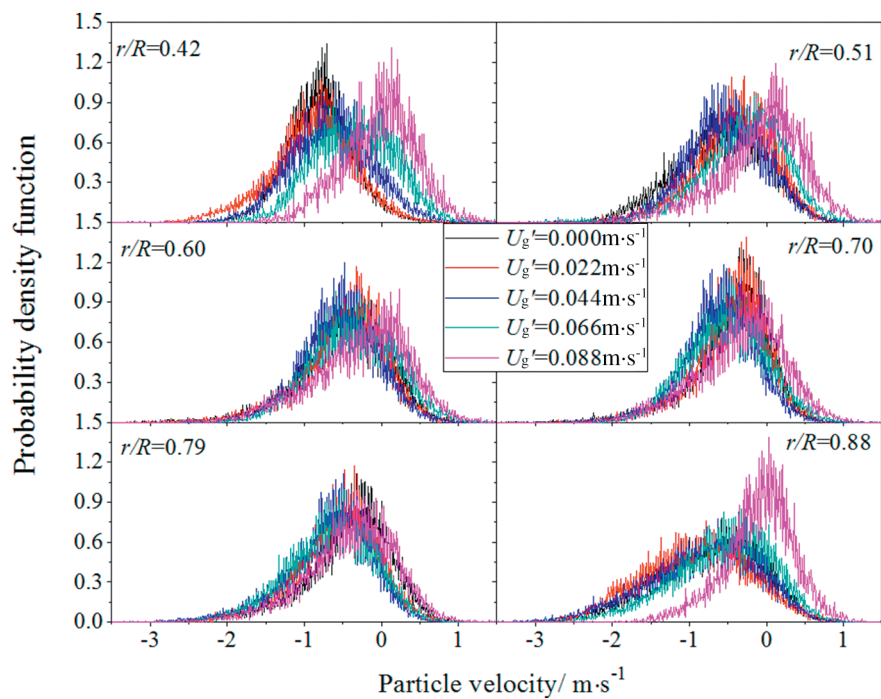


Fig. 13. Effect of superficial stripping gas velocity on probability density function of particle velocity at different radial positions ($U_g = 1.57 \text{ m}\cdot\text{s}^{-1}$, $G_s = 4.42 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $H = 2.72 \text{ m}$).

$0.74 < r/R \leq 0.93$. Correlations of all the data in Table 1, according to Eq. (2), by Max Implementation Optimization (MIO) method led to

$$\frac{V_p}{V_p} = 0.047 \left(\frac{r}{R}\right)^{-1.771} \left(\frac{G_s}{\rho_p U_g}\right)^{-0.244} (Fr_{dp} + 2.766)^{0.127} \quad (0.42 \leq r/R \leq 0.56) \tag{3}$$

$$\frac{V_p}{V_p} = 0.100 \left(\frac{r}{R}\right)^{-0.380} \left(\frac{G_s}{\rho_p U_g}\right)^{-0.283} (Fr_{dp} + 0.483)^{-0.105} \quad (0.56 < r/R \leq 0.74) \tag{4}$$

$$\frac{V_p}{V_p} = 6.833 \frac{r^{4.893}}{R} \left(\frac{G_s}{\rho_p U_g}\right)^{0.180} (Fr_{dp} + 0.385)^{0.026} \quad (0.74 < r/R \leq 0.93) \tag{5}$$

To test the predictive abilities of these correlations, Eqs. (3)–(5) were verified against independent data obtained under different opera-

tion conditions given in Table 2. By comparing the calculated values with the experimental data used to establish the empirical formula and the independent data, Fig. 14 showed that Eqs. (3)–(5) had an average relative error of 12.47% which implied great performance in predicting the dimensionless quantity $\frac{V_p}{V_p}$.

4. Conclusions

The radial profiles of particle velocity in a large scale annular stripper were studied with the help of a laser Doppler velocimetry (LDV) system. The particle movement directions at almost all of the radial positions were the same as the direction of gravity within the experimental operating range. Particle velocity radial profiles exhibited a relatively stable mid-region ($r/R = 0.56\text{--}0.84$), while in the wall region on both sides of the stripper ($r/R < 0.56$ or $r/R > 0.84$) the particle descent velocity gradually increased towards the stripper walls.

The effect of different operating conditions on particle velocity distribution was obvious. When superficial gas velocity enlarged from 1.57 to $2.20 \text{ m}\cdot\text{s}^{-1}$ (under a constant solid mass flux of $4.42 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), particle descent velocity increased at every radial position, especially in the mid-region of the stripper. Moreover, with solid mass flux ranging from 4.42 to $12.61 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the maximum of particle descent velocity in the outer wall region increased obviously and the radial profiles became more non-uniform. Furthermore, stripping gas velocity had a tremendous influence on particle descent velocity and particle velocity radial profiles. The effect of stripping gas velocity on the radial profiles near the stripper gas distributor was quite obvious and gradually diminished away from the distributor. Because of the special geometry of the stripping distributor and the increase of the stripping gas velocity, uniform or U-shaped radial distribution was observed in the lower levels of the stripper.

Based on effects of the superficial gas velocity, solid mass flux, and stripping gas velocity, empirical formulas were developed for predicting the $\frac{V_p}{V_p}$ in the annular stripper. Upon examination, the calculated results of these formulas agreed well with the experimental data.

Table 1
Operating conditions for fitting correlations

$U_g/\text{m}\cdot\text{s}^{-1}$	$U_g'/\text{m}\cdot\text{s}^{-1}$	$G_s/\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	H/m
1.57	0.000, 0.044, 0.088	4.42	2.92–3.22
1.89	0.000, 0.044, 0.088	4.42	2.92–3.22
2.20	0.000, 0.044, 0.088	4.42, 8.10, 12.61	2.92–3.22

Table 2
Operating conditions used in verifying experiment

$U_g/\text{m}\cdot\text{s}^{-1}$	$U_g'/\text{m}\cdot\text{s}^{-1}$	$G_s/\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	H/m
1.57	0.022, 0.066	4.42	2.92–3.22
1.89	0.022, 0.066	4.42	2.92–3.22
2.20	0.022, 0.066	4.42, 8.10, 12.61	2.92–3.22

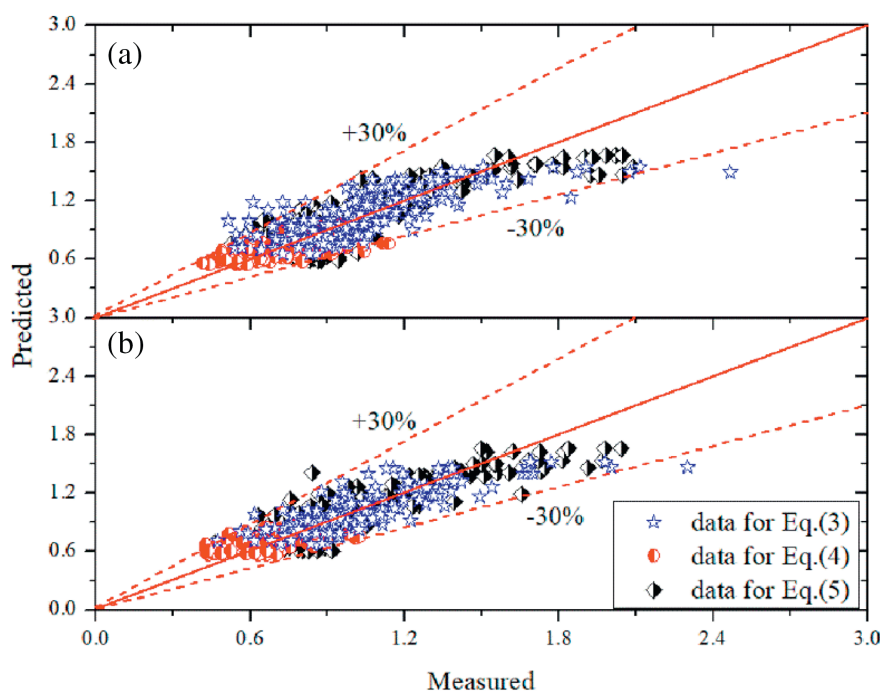


Fig. 14. Comparison of prediction with (a) the experimental data used to develop the correlation and (b) independent experimental data.

References

- [1] J.W. Chen, H.C. Cao, Catalytic Cracking Technology and Engineering, China Petrochemical Press, Beijing, 2015 (in Chinese).
- [2] H.T. Bi, N. Ellis, I.A. Abba, J.R. Grace, A state-of-the-art review of gas–solid turbulent fluidization, *Chem. Eng. Sci.* 55 (21) (2000) 4789–4825.
- [3] Y. Cheng, C. Wu, J. Zhu, F. Wei, Y. Jin, Downer reactor: From fundamental study to industrial application, *Powder Technol.* 183 (3) (2008) 364–384.
- [4] D. Li, M.B. Ray, A.K. Ray, J. Zhu, A comparative study on hydrodynamics of circulating fluidized bed riser and downer, *Powder Technol.* 247 (10) (2013) 235–259.
- [5] C. Wang, C. Li, J. Zhu, C. Wang, S. Barghi, J. Zhu, A comparison of flow development in high density gas–solids circulating fluidized bed downer and riser reactors, *AIChE J.* 61 (4) (2015) 1172–1183.
- [6] J.X. Zhu, Z.Q. Yu, Y. Jin, J.R. Grace, A. Issangya, Cocurrent downflow circulating fluidized bed (downer) reactors – A state of the art review, *Can. J. Chem. Eng.* 73 (5) (1995) 662–677.
- [7] T. McKeen, T. Pugsley, Simulation of cold flow FCC stripper hydrodynamics at small scale using computational fluid dynamics, *Int. J. Chem. React. Eng.* 1 (2003) A18.
- [8] H. Bi, H. Cui, J. Grace, A. Kern, C.J. Lim, D. Rusnell, X. Song, C. McKnight, Flooding of gas–solids counter-current flow in fluidized beds, *Ind. Eng. Chem. Res.* 43 (18) (2004) 5611–5619.
- [9] H.T. Bi, J.R. Grace, C.J. Lim, D. Rusnell, D. Bulbuc, C.A. McKnight, Hydrodynamics of the stripper section of fluid cokers, *Can. J. Chem. Eng.* 83 (2) (2005) 161–168.
- [10] H.P. Cui, M. Strabel, D. Rusnell, H.T. Bi, K. Mansaray, J.R. Grace, C.J. Lim, C.A. McKnight, D. Bulbuc, Gas and solids mixing in a dynamically scaled fluid coker stripper, *Chem. Eng. Sci.* 61 (2) (2006) 388–396.
- [11] J. Gao, J. Chang, X. Lan, Y. Yang, C. Lu, C. Xu, CFD modeling of mass transfer and stripping efficiency in FCCU strippers, *AIChE J.* 54 (5) (2008) 1164–1177.
- [12] H. Sun, M. Cheng, D. Chen, L. Xu, Z. Li, N. Cai, Experimental study of a carbon stripper in solid fuel chemical looping combustion, *Ind. Eng. Chem. Res.* 54 (35) (2015) 8743–8753.
- [13] H. Sun, M. Cheng, Z. Li, N. Cai, Riser-based carbon stripper for coal-fueled chemical looping combustion, *Ind. Eng. Chem. Res.* 55 (8) (2016) 2381–2390.
- [14] G.K. Veluswamy, R.K. Upadhyay, R.P. Utikar, G.M. Evans, M.O. Tade, M.E. Glenn, S. Roy, V.K. Pareek, Hydrodynamics of a fluid catalytic cracking stripper using γ -ray densitometry, *Ind. Eng. Chem. Res.* 50 (10) (2011) 5933–5941.
- [15] D. Jia, H. Zhao, A.S. Berrouk, C. Yang, H. Shan, Numerical study of counter-current gas–solid flow in FCC disengager and stripper, *Can. J. Chem. Eng.* 92 (1) (2014) 176–188.
- [16] G.K. Veluswamy, R.K. Upadhyay, R.P. Utikar, M.O. Tade, G. Evans, M.E. Glenn, S. Roy, V.K. Pareek, Hydrodynamic study of fluid catalytic cracker unit stripper, *Ind. Eng. Chem. Res.* 52 (12) (2013) 4660–4671.
- [17] J. Gao, J. Chang, C. Xu, X. Lan, Y. Yang, CFD simulation of gas solid flow in FCC strippers, *Chem. Eng. Sci.* 63 (7) (2008) 1827–1841.
- [18] Y. Liu, X. Lan, C. Xu, G. Wang, J. Gao, CFD simulation of gas and solids mixing in FCC strippers, *AIChE J.* 58 (4) (2012) 1119–1132.
- [19] D.H. Van Wagener, G.T. Rochelle, Stripper configurations for CO₂ capture by aqueous monoethanolamine, *Chem. Eng. Res. Des.* 89 (9) (2011) 1639–1646.
- [20] I. Rose, H. Cui, T. Zhang, C. McKnight, J. Grace, X. Bi, J. Lim, Towards an ultimate fluidized bed stripper, *Powder Technol.* 158 (1) (2005) 124–132.
- [21] M. Karimi, M. Hillestad, H.F. Svendsen, Capital costs and energy considerations of different alternative stripper configurations for post combustion CO₂ capture, *Chem. Eng. Res. Des.* 89 (8) (2011) 1229–1236.
- [22] Y. Zhang, C. Lu, M. Shi, Large-scale cold pilot experiment on a new annular catalyst stripper for FCC units, *J. Chem. Eng. Chin. Univ.* 18 (3) (2004) 377–380 (in Chinese).
- [23] H. Cui, J. Grace, C. McKnight, T. Zhang, I. Rose, X. Bi, J. Lim, D. Burgardt, Jet configuration for improved fluidized bed stripping, *Chem. Eng. J.* 125 (1) (2006) 1–8.
- [24] G. Li, D. Gao, J. Shi, A new stripping column process and optimization of its operation, *Chem. Eng. Technol.* 39 (12) (2016) 2229–2237.
- [25] J. Werther, B. Hage, C. Rudnick, A comparison of laser Doppler and single-fibre reflection probes for the measurement of the velocity of solids in a gas–solid circulating fluidized bed, *Chem. Eng. Process.* 35 (5) (1996) 381–391.
- [26] C.H. Ipsen, T. Solberg, B.H. Hjertager, F. Johnsson, Laser Doppler anemometry measurements in a circulating fluidized bed of metal particles, *Exp. Thermal Fluid Sci.* 26 (6) (2002) 851–859.
- [27] Y. Lu, D.H. Glass, W.J. Easson, An investigation of particle behavior in gas–solid horizontal pipe flow by an extended LDA technique, *Fuel* 88 (12) (2009) 2520–2531.
- [28] Z. Qian, M. Zhang, H. Yu, F. Wei, Radial profiles of particle velocity in a large scale CFB downer, *Int. J. Chem. React. Eng.* 2 (2004) A7.
- [29] Y. Wang, F. Wei, Z. Wang, Y. Jin, Y. Zhiqing, Radial profiles of solids concentration and velocity in a very fine particle (36 μ m) riser, *Powder Technol.* 96 (3) (1998) 262–266.
- [30] F. Wei, H. Lin, Y. Cheng, Z. Wang, Y. Jin, Profiles of particle velocity and solids fraction in a high-density riser, *Powder Technol.* 100 (2) (1998) 183–189.
- [31] Y. Li, T. Li, H. Zhang, Q. Sun, W. Ying, LDV measurements of particle velocity distribution and annular film thickness in a turbulent fluidized bed, *Powder Technol.* 305 (2017) 578–590.
- [32] A. Mychkovsky, D. Rangarajan, S. Ceccio, LDV measurements and analysis of gas and particulate phase velocity profiles in a vertical jet plume in a 2D bubbling fluidized bed: Part I: A two-phase LDV measurement technique, *Powder Technol.* 220 (4) (2012) 55–62.
- [33] B. Wang, T. Li, Q.W. Sun, W.Y. Ying, D.Y. Fang, Experimental study on flow behavior in a gas–solid fluidized bed for the methanol-to-olefins process, *Chem. Eng. Technol.* 33 (10) (2010) 1591–1600.
- [34] S. Li, W. Lin, J. Yao, Modeling of the hydrodynamics of the fully developed region in a downer reactor, *Powder Technol.* 145 (2) (2004) 73–81.
- [35] B. Wu, J.X. Zhu, L. Briens, A comparison of flow dynamics and flow structure in a riser and a downer, *Chem. Eng. Technol.* 30 (4) (2007) 448–459.
- [36] M. Zhang, Z. Qian, H. Yu, F. Wei, The near wall dense ring in a large-scale down-flow circulating fluidized bed, *Chem. Eng. J.* 92 (1) (2003) 161–167.
- [37] Y. Yang, Y. Jin, Z. Yu, Z. Wang, Particle flow patterns in the riser and downer of circulating fluidized bed, *Chin. J. Chem. Eng.* 7 (2) (1992) 164–172.
- [38] W. Wang, J. Li, Simulation of gas–solid two-phase flow by a multi-scale CFD approach – Of the EMMS model to the sub-grid level, *Chem. Eng. Sci.* 62 (1) (2007) 208–231.
- [39] N. Yang, W. Wang, W. Ge, J. Li, Analysis of flow structure and calculation of drag coefficient for concurrent-up gas–solid flow, *Chin. J. Chem. Eng.* 11 (1) (2003) 79–84.
- [40] C.S. Campbell, Rapid granular flows, *Annu. Rev. Fluid Mech.* 22 (22) (1990) 57–90.
- [41] Z. Wang, D. Bai, Y. Jin, Hydrodynamics of cocurrent downflow circulating fluidized bed (CDCFB), *Powder Technol.* 70 (3) (1992) 271–275.
- [42] M. Zhang, Z. Qian, F. Wei, Y. Jin, Study on radial solid-fraction profiles in large-scale downer reactor, *J. Chem. Eng. Chin. Univ.* 16 (6) (2002) 621–625 (in Chinese).