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Concentration profile of jet gas in the feed injection zone of a FCC riser

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Abstract

The concentration profiles of jet gas are investigated in the feed injection zone of a cold-model FCC riser by using a hydrogen trace technique. Experimental results demonstrate that four types of jet gas concentration profiles can be used to describe the mixing between the jet gas and pre-lift gas in the feed injection zone. The four types are a distinct M-shaped profile for weak mixing, an indistinct M-shaped profile for medium mixing, a sharp profile for strong mixing, and a parabolic profile for full mixing. The heights for regions of initial and full mixing reduce when decreasing the jet gas velocity or increasing the pre-lift gas velocity. Furthermore, the momentum ratio, M_j/M_r, (where M_j is the momentum of jet gas, M_r is the mixture momentum of pre-lift gas and solid particles) is introduced to describe the effects of gas–solid physical properties, operating conditions, and equipment configuration on the jet gas concentration distribution. The heights for regions of initial and full mixing between jet gas and pre-lift gas are found to be 0–0.375 and 0.375–0.675 m when $M_j/M_r < 0.29$, 0.375–0.675 and 1.075–1.375 m when $M_j/M_r > 0.54$, and 0–0.375 and 0.675–1.075 m when M_j/M_r between 0.29 and 0.54, respectively.

Keywords: FCC riser; Feed injection zone; Jet gas concentration; Momentum ratio

1. Introduction

A riser reactor is one of the most important units in fluid catalytic cracking (FCC) process, which has been widely used in the modern petroleum refinery industry [1]. In this FCC unit, catalysts enter the bottom of the riser from the regenerator. These catalyst particles are then conveyed by a pre-lift gas steam to the feed injection zone, where catalysts meet the feed oil gas injected through atomizing nozzles and a rapid chemical reaction between jet gas and catalyst particles occurs [1]. Atomization of feed oil gas, concentration distribution of feed oil gas, mixing between feed oil gas and pre-lift gas, as well as mixing between feed oil gas and catalyst particles have a great impact on this chemical reaction.

In the past two decades, Werther et al. [2], Amos et al. [3], Gayfin et al. [4], and Sterneus et al. [5] experimentally investigated gas mixing behavior in the riser based on the radial profiles of gas concentration, while Thelogs et al. [6], Subramanya et al. [7], Gupta and Rao [8,9], and Gao et al. [10] numerically simulated the atomization effect of feed oil gas in the feed injection zone on FCC riser performance. There are few reports on the analysis of complex three-phase flow of feed oil gas, pre-lift gas and catalyst particles in the feed injection zone of the riser. To our knowledge, only Fan et al. [11–14] investigated the oil gas concentration profiles in the feed injection zone and proposed two types of feedstock injection structures by using the relative oil gas concentration distribution [13,14]. However, actual feed oil gas concentration distribution in the feed injection zone has advantages over its relative value for developing a new type of FCC reactors and improving the existing units.

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Actual feed oil gas phase concentration is adopted in this study rather than relative concentration when using a hydrogen tracer technique. The radial profiles of actual feed oil gas concentration are investigated at different axial positions in the feed injection zone of a riser at different jet gas velocities and pre-lift gas velocities. Furthermore, a new parameter, defined as the ratio of the momentum of feed oil gas to the mixture momentum of pre-lift gas and solid particles, is proposed to describe the effects of physical properties of gas and solid, operating conditions, and equipment configuration on the feed oil gas concentration distribution.

2. Measurement method and experimental set-up

2.1. Measurement method

Gas tracer technique, an effective method for measuring the gas concentration profiles and mixing behavior in the gas–solid fluidized bed [2–5,11–16], was employed in this study to investigate the concentration distribution of the feed oil gas in the FCC riser feed injection zone. Hydrogen as a gas tracer was injected into the nozzles in pulse method and then the nozzle jet gas brought hydrogen into the riser [11–14]. Because hydrogen injection time was quite short and the flux of tracer was far less than that of pre-lift gas or jet gas, it is difficult to measure accurately hydrogen concentration. In order to systemically reduce measurement errors and noises due to intensive turbulence in the feed zone, an eigenconcentration of jet gas, i.e., feed oil gas, was introduced by Fan et al. [11–14] as follows

$$C_1 = \frac{c_i}{\sum_1^n c_i}\left(\frac{Q_i}{Q_j + Q_r}\right) \tag{1}$$

where C_i stands for the eigenconcentration of the jet gas at the *i*th radial position, c_i for the sampling tracer concentration, Q_j and Q_r for the volume flow rates of the jet gas and pre-lift gas, respectively. It is noted that the sampling tracer concentration obtained directly from samples is the hydrogen concentration in the gas phase, but it does not represent the concentration in gas–solid two-phase flow. Based on the concept of eigenconcentration, Fan et al. [11–14] calculated the relative concentration of the jet gas as follows

$$C_{i0} = \frac{C_i}{\mathrm{Max}C_i} \tag{2}$$

where $\mathrm{Max}\,C_i$ is the maximum value of C_i.

In this study, a new parameter is proposed to describe the actual concentration distribution of the jet gas, i.e., feed oil gas, in a riser feed injection zone, which is expressed as

$$C_{i1} = C_{i2}\varepsilon_i = \frac{Q_\mathrm{j}\varepsilon_\mathrm{a}c_i\varepsilon_i}{2(Q_\mathrm{j} + Q_\mathrm{r})\int_0^1 c_i\varepsilon_i\phi\mathrm{d}\phi} \tag{3}$$

where φ is the dimensionless radial position, $\varphi = r/R$; ε_i is the local voidage, and ε_a is the averaged cross-section voidage obtained from integration of ε_i along the cross-section. In the above equation, C_{i2} represents the actual jet gas concentration in gas phase, and C_{i1} represents the actual jet gas concentration in gas and solid phases.

Fig. 1 keep (a) and (b) shows the radial profiles of C_{i0} from Eq. (2) and C_{i1} from Eq. (3), respectively, at a height of $H = 0.675$ m when the pre-lift gas velocity ranges from 2.25 to 4.30 m/s. It can be seen that C_{i0} keeps a constant of 1 at the riser center ($r/R = 0$) for all three different pre-lift gas velocities. A slight increase in the relative jet gas concentration can be seen at r/R of less than 0.75, when the pre-lift gas velocity increases from 2.25 to 4.30 m/s in Fig. 1 keep (a). In contrast, the actual jet gas concentration in the gas and solid phases, C_{i1}, gradually decreases at all radial positions with the increasing pre-lift gas velocity, when the jet gas velocity keeps constant as shown in Fig. 1 keep (b).

The average cross-sectional jet gas concentration, C_a, is obtained by integrating jet gas relative (C_{i0}) and actual (C_{i1}) concentration along the radial distribution, and the calculation results at a height of $H = 0.675$ m are shown

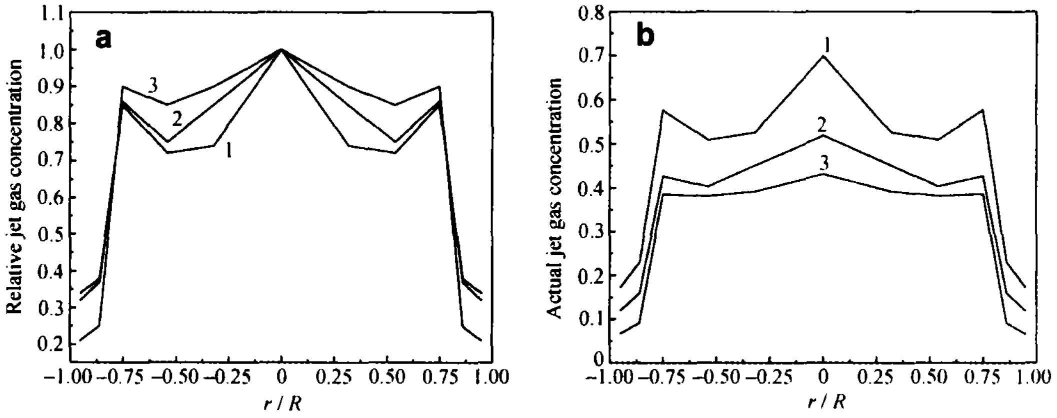

Fig. 1. The radial profiles of the jet gas concentration for different pre-lift gas velocities (the axial height above the nozzles H is 0.675 m, the jet gas velocity U_j is 41.7 m/s). Curves 1–3 represent jet gas concentration at the pre-lift gas velocity U_r of 2.25, 3.28, and 4.30 m/s, respectively. (a) The relative jet gas concentration from Eq. (2), (b) actual jet gas concentration from Eq. (3).

in Fig. 2. When the jet gas velocity increases from 41.7 to 83.3 m/s while the pre-lift gas velocity keeps constant as shown in Fig. 2 keep (a), the average cross-section jet gas concentration increases by using parameter C_{i1}. The average concentration obtained from parameter C_{i0}, however, gives a contrary tendency. Similar phenomena can be observed from Fig. 2 keep (b), when the pre-lift gas velocity decreases but jet gas velocity keeps constant. The average cross-section jet gas concentration from C_{i1} increases while decreases from the parameter C_{i0}.

Furthermore, the average cross-section jet gas volume flux, Q_o, can be calculated by the average cross-section jet gas concentration and the average interstitial gas volume flux as

$$Q_0 = \frac{c_a}{\epsilon_a} \times (Q_j + Q_r) \tag{4}$$

The calculated average cross-section jet gas volume fluxes (Q_{o1} from relative jet gas concentration and Q_{o2} from actual jet gas concentration) are summarized in Table 1. The experimentally measured jet gas volume flux is compared to the two calculated values, Q_{o1} and Q_{o2}. It can be found that the maximum relative error is up to 94.3% and the average relative error is 30.0% by using the method proposed by Fan et al. [12–15]. In contrast, the maximum and average relative errors decrease to 4.2% and 2.6%, respectively, by the modified method in this study.

The above comparisons of the radial distribution of jet gas concentration, average cross-section jet gas concentration, and average cross-section jet gas volume flux indicate that C_{i1} suggested in this study is more reasonable than C_{i0} in the Refs. [11–14] to describe the jet gas concentration in the feed injection zone of a FCC riser.

2.2. Experimental set-up

A schematic diagram of the experimental setup used in this study is shown in Fig. 3. The riser vessel consists of a series of 186 mm I.D. flanged plexiglass pipes with a height of 12 m. Four nozzles equivalent to the atomizing nozzles in the FCC unit are located at a height of 4.5 m above the pre-lift gas distributor and installed with an angle of 30° relative to the riser axis. The hydrogen tracer technique is employed to measure the concentration distribution of the jet gas in the feed injection zone of the riser. FCC catalysts are used as solid particles. Both jet gas and pre-lift gas are air. All the experiments are carried out at atmospheric pressure

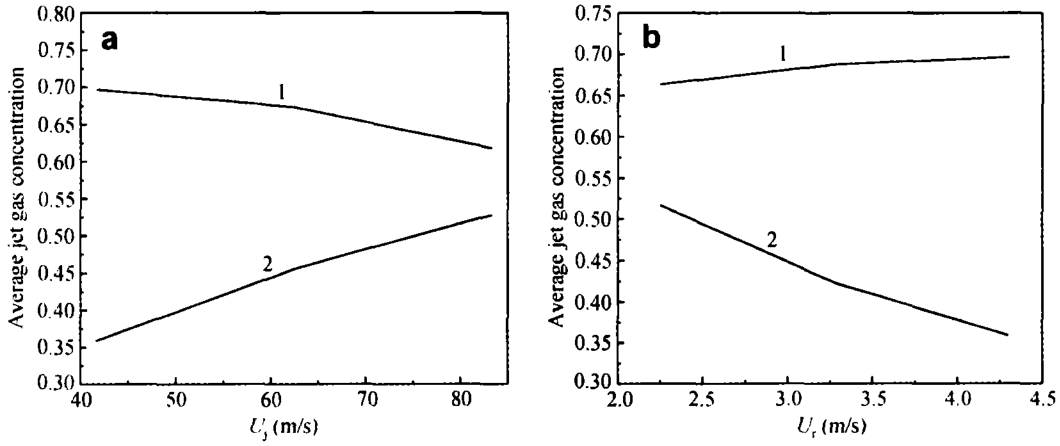

Fig. 2. The average cross-section jet gas concentration by varying the jet gas velocity and pre-lift gas velocity. Curve 1 represents the average jet gas concentration from Eq. (2); curve 2 is for the average jet gas concentration from Eq. (3). (a) The average concentration versus jet gas velocities while keeping pre-lift gas velocity constant ($H = 0.675$ m, $U_r = 4.30$ m/s), (b) the average concentration versus pre-lift gas velocities while keep jet gas velocity constant ($H = 0.675$ m, $U_j = 41.7$ m/s).

Table 1
Comparison between the measured and calculated jet gas volume flux

U_r (m/s)	U_j (m/s)	Exp.	Refs. [11–14]		This study	
		Q_j (m^3/h)	Q_{o1} (m^3/h)	Error (%)	Q_{o2} (m^3/h)	Error (%)
2.25	41.7	240.2	308.6	28.5	248.6	3.5
2.25	62.5	360.0	363.2	0.9	366.3	1.8
2.25	83.3	479.8	431.1	10.2	492.9	2.7
3.28	41.7	240.2	390.7	62.7	250.4	4.2
3.28	62.5	360.0	451.3	25.4	368.7	2.4
3.28	83.3	479.8	529.7	10.4	485.2	1.1
4.30	41.7	240.2	466.6	94.3	247.1	2.9
4.30	62.5	360.0	531.6	47.7	370.5	2.9
4.30	83.3	479.8	562.4	17.2	489.5	2.0

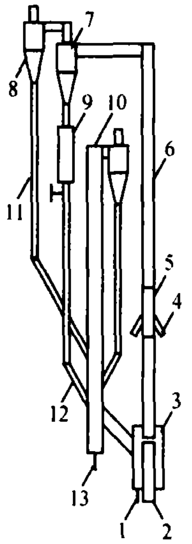

Fig. 3. Schematic diagram of the experimental apparatus. (1) Inlet of auxiliary fluidizing gas, (2) inlet of pre-lift gas, (3) pre-lift section, (4) nozzles, (5) feed injection zone, (6) riser vessel, (7) first stage cyclone, (8) secondary stage cyclone, (9) vessel for measuring solid flux, (10) downcomer, (11) dipleg of secondary stage cyclone, (12) dipleg of first stage cyclone, and (13) inlet of fluidizing gas.

and a room temperature of approximately 25 °C. The operating conditions for pre-lift gas velocity, nozzle jet gas velocity, and solid flux are in the range of 2.25–4.30 m/s, 41.7–83.3 m/s, and 60–113 kg/m^{2}s, respectively.

3. Results and discussion

3.1. Jet gas concentration profiles at different axial positions

Fig. 4 shows the radial profiles of the jet gas concentration at different axial heights for two sets of the jet gas velocity and pre-lift gas velocity. At U_r of 2.25 m/s and U_j of 62.5 m/s, as shown in Fig. 4a, a distinct M-shaped profile of the jet gas concentration is observed at a height of $H = 0.375$ m. This indicates that the majority of the jet gas passes in the middle region ($r/R = 0.32$–0.54) of the riser, while the majority of the pre-lift gas flows in the center regions ($r/R = 0$–0.32) and close to the wall ($r/R \geqq 0.95$). Mixing between jet gas and pre-lift gas is quite weak at this axial position. At heights of $H = 0.675$ m and $H = 1.075$ m, on the other hand, a sharp profile of the jet gas concentration, a sharp increase in the center ($r/R = 0$) and a gradual decrease in the middle region ($r/R = 0.32$–0.54) indicate that mixing between the two gas phases becomes gradually intensive. Up to the height of $H = 1.375$ m, a parabolic profile of the jet gas concentration means full mixing of jet gas with pre-lift gas, because this profile is similar to the voidage profile before the jet gas is introduced into the riser.

At U_r of 3.28 m/s and U_j of 41.7 m/s as shown in Fig. 4b, an indistinct M-shaped profile of jet gas concentration can be seen at a height of $H = 0.375$ m, where the concentration of jet gas increases at the center ($r/R = 0$) and decreases in the middle region ($r/R = 0.32$–0.54), compared with that at the same section in Fig. 4a. This profile indicates that jet gas partially enters into the center region ($r/R = 0$) of the riser and the mixing of jet gas with pre-lift gas at both given jet gas velocity and pre-lift gas velocity becomes stronger under this operating condition. At a height of $H = 0.675$ m, the concentration profile of jet gas is similar to that in Fig. 4a at the same height. Mixing between the two gas phases becomes gradually stronger as the height increases. Above a height of $H = 1.075$ m, full mixing has been realized but this mixing pattern can only be seen at a height of 1.375 m in Fig. 4a.

It is apparent that there exist four types of jet gas concentration profiles as shown in Fig. 4 to describe different mixing intensities between jet gas and pre-lift gas in the feed injection zone of a riser. A distinct M-shaped profile stands for very weak mixing, an indistinct M-shaped profile for medium mixing, a sharp profile for strong mixing, and a parabolic profile for full mixing.

3.2. Effects of jet gas velocity

The jet gas concentration is described in Fig. 4 at two different sets of jet gas velocity and pre-lift gas velocity. The change of jet gas velocity and pre-lift gas velocity is investi-

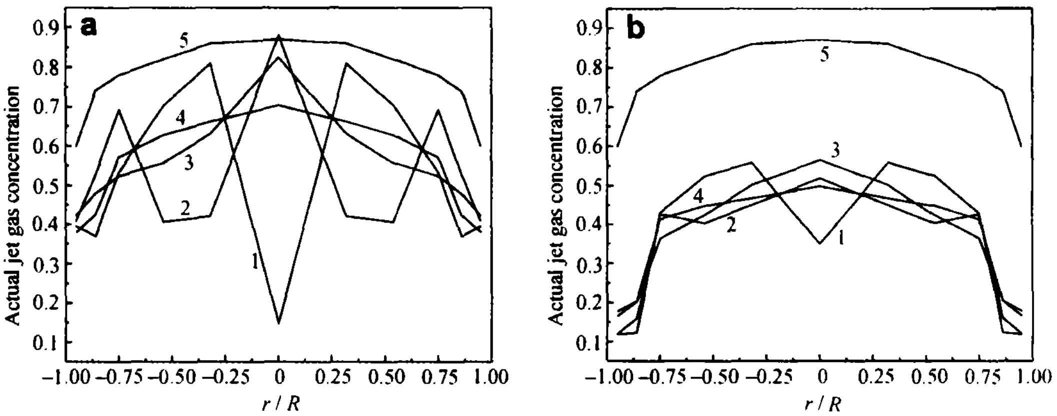

Fig. 4. Radial profiles of jet gas concentration at different axial heights. Curves 1–4 represent the jet gas concentration at $H = 0.375$, 0.675, 1.075, 1.375 m, respectively; curve 5 is for the voidage at $H = 1.375$ m before jet gas enters the riser. (a) $U_j = 62.5$ m/s, $U_r = 2.25$ m/s, (b) $U_j = 41.7$ m/s, $U_r = 3.28$ m/s.

gated in this and the following sections. When pre-lift gas velocity is fixed at 4.30 m/s and jet gas velocity increases from 41.7 to 83.3 m/s, the radial profiles of jet gas concentration at different heights are shown in Fig. 5. At the section of $H = 0.375$ m as shown in Fig. 5a, as jet gas velocity reduces from 83.3 to 41.7 m/s, the concentration of jet gas decreases in the regions of r/R from 0.32 to 0.95, while increases at the center of $r/R = 0$. Changes in the concentration profiles of jet gas from a distinct M-shape (poor mixing) to an indistinct M-shape (medium mixing) with decreasing jet gas velocity indicate that slow jet gas velocity can improve mixing in this section. At a height of $H = 1.075$ m, a decrease of jet gas velocity results in reduction of jet gas concentration at all radial positions, and changes from a sharp profile for strong mixing to a parabolic profile for full mixing (Fig. 5b). It can be seen from Fig. 5 that the jet gas velocity has a great impact on mixing intensity at different heights. When the jet gas velocity is smaller than 41.7 m/s, initial and full mixing between jet gas and pre-lift gas occur in the feed injection zone of a riser at a height of 0–0.375 m and 0.675–1.075 m, respectively. However, when the jet gas velocity is greater than 41.7 m/s, the heights for initial and full mixing change to 0.375–0.675 m and 1.075–1.375 m, respectively. The jet gas velocity of about 41.7 m/s is found to be a transitional point, which can account for different mixing characteristics between jet gas and pre-lift gas at different heights.

3.3. Effects of pre-lift gas velocity

By varying pre-lift gas velocity from 2.25 to 4.30 m/s while keeping a constant jet gas velocity of 41.7 m/s, the effect of pre-lift gas velocity on radial profiles of jet gas concentration is shown in Fig. 6. At a height of $H = 0.375$ m, when pre-lift gas velocity increases, a decrease of jet gas concentration in the radial region of $r/R = 0.32$–0.95 and an increase at the center ($r/R = 0$) can be observed in Fig. 6a. This observation suggests the transformation of jet gas concentration profile from a distinct M-shape for very weak mixing to an indistinct M-shape for medium mixing, which is found at a transitional pre-lift gas velocity of about 3.28 m/s. In contrast, at a height of $H = 1.075$ m, as shown in Fig. 6b, the jet gas concentration profile changes from a sharp profile for strong mixing to a parabolic profile for full mixing with increasing pre-lift gas velocity, which is similar to that with decreasing jet gas velocity in Fig. 5b. A similar conclusion can be drawn that

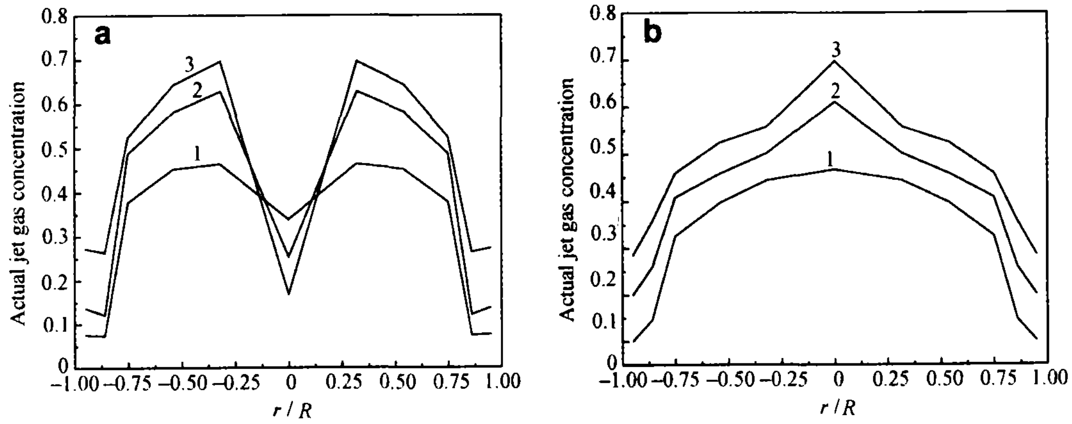

Fig. 5. Effects of jet gas velocity on jet gas concentration profiles. Curves 1–3 represent jet gas concentration at $U_j = 41.7$, 62.5, and 83.3 m/s, respectively. (a) $H = 0.375$ m, $U_r = 4.30$ m/s, (b) $H = 1.075$ m, $U_r = 4.30$ m/s.

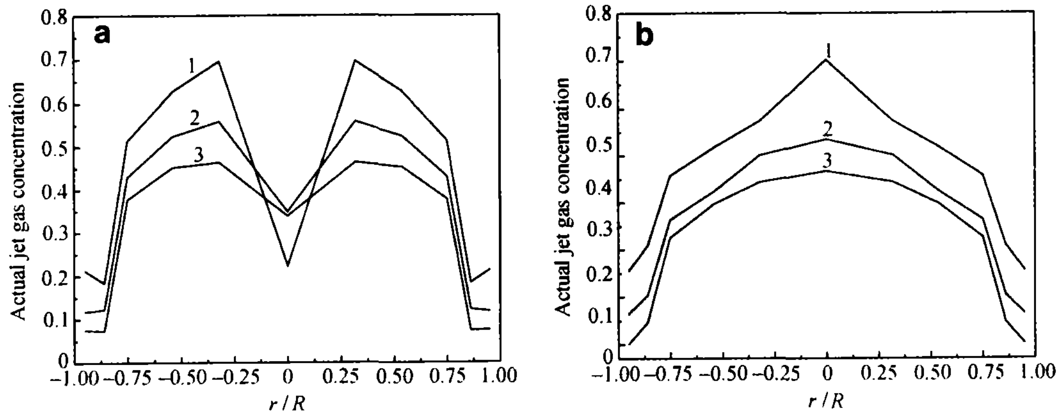

Fig. 6. Effects of pre-lift gas velocity on jet gas concentration profiles. Curves 1–3 represent jet gas concentration at $U_r = 2.25$, 3.28, and 4.30 m/s, respectively. (a) $H = 0.375$ m, $U_j = 41.7$ m/s, (b) $H = 1.075$ m, $U_j = 41.7$ m/s.

the transitional pre-lift gas velocity is around 3.28 m/s under this operating condition.

The heights for initial and full mixing between jet gas and pre-lift gas are about 0–0.375 m and 0.675–1.075 m, respectively in the feed injection zone of a riser when the pre-lift gas velocity is greater than 3.28 m/s, while they are 0.375–0.675 and 1.075–1.375 m when pre-lift gas velocity is smaller than 3.28 m/s.

3.4. *Effects of momentum ratio*

Besides jet gas velocity and pre-lift gas velocity discussed above, other parameters, such as solid phase flux, solid phase velocity, cross-section areas of the nozzle and the riser, and number of nozzles, have an effect on jet gas concentration in the feed injection zone of a riser. In order to investigate the influences of these parameters, a momentum ratio, defined as the ratio of the momentum of jet gas, M_j, to the mixture momentum of pre-lift gas and solid particles, M_r, is proposed as follows

$$\frac{M_j}{M_r} = \frac{N\rho_j U_j^2 A_j}{\rho_r U_r^2 A_r + G_s U_p A_r} \tag{5}$$

where A_j and A_r are the cross-section areas of each nozzle and a riser, respectively, N is the number of nozzles, ρ_j and ρ_r are the densities of jet gas, and pre-lift gas respectively, G_s is solid phase flux, and U_p is solid phase velocity.

The effects of the momentum ratio on jet gas concentration at different heights in a riser are shown in Fig. 7. At a height of $H = 0.375$ m, jet gas concentration decreases in the riser except at the center ($r/R = 0$) with a decrease of the momentum ratio as shown in Fig. 7 keep (a). The concentration of jet gas is a distinct M-shaped distribution for very weak mixing when the momentum ratio is greater than 0.54, while it becomes an indistinct M-shaped distribution for medium mixing when the momentum ratio is smaller than 0.54. Therefore, the transitional momentum ratio can be found to be about 0.54. At the heights of $H = 0.675$ m and $H = 1.075$ m, the jet gas concentration changes from a sharp distribution for strong mixing to a parabolic profile for full mixing with a decrease of the momentum ratio as illustrated in Fig. 7 keep (b) and keep (c). The transitional momentum ratio is about 0.29 at $H = 0.675$ m, while it is 0.54 at $H = 1.075$ m. Up to the height of $H = 1.375$ m, as shown in Fig. 7 keep (d), the concentration profiles of jet gas are all parabolic for full mixing for the momentum ratio ranging from 0.29 to 4.21.

In Fig. 7, the regions for initial and full mixing between jet gas and pre-lift gas are dependent on the momentum ratio. The regions inside a riser for initial and full mixing are: (i) about 0–0.375 and 0.375–0.675 m, respectively, when the momentum ratio is smaller than 0.29; (ii) about 0–0.375 and 0.675–1.075 m, respectively, when the momentum ratio ranges from 0.29 to 0.54; and (iii) about 0.375–

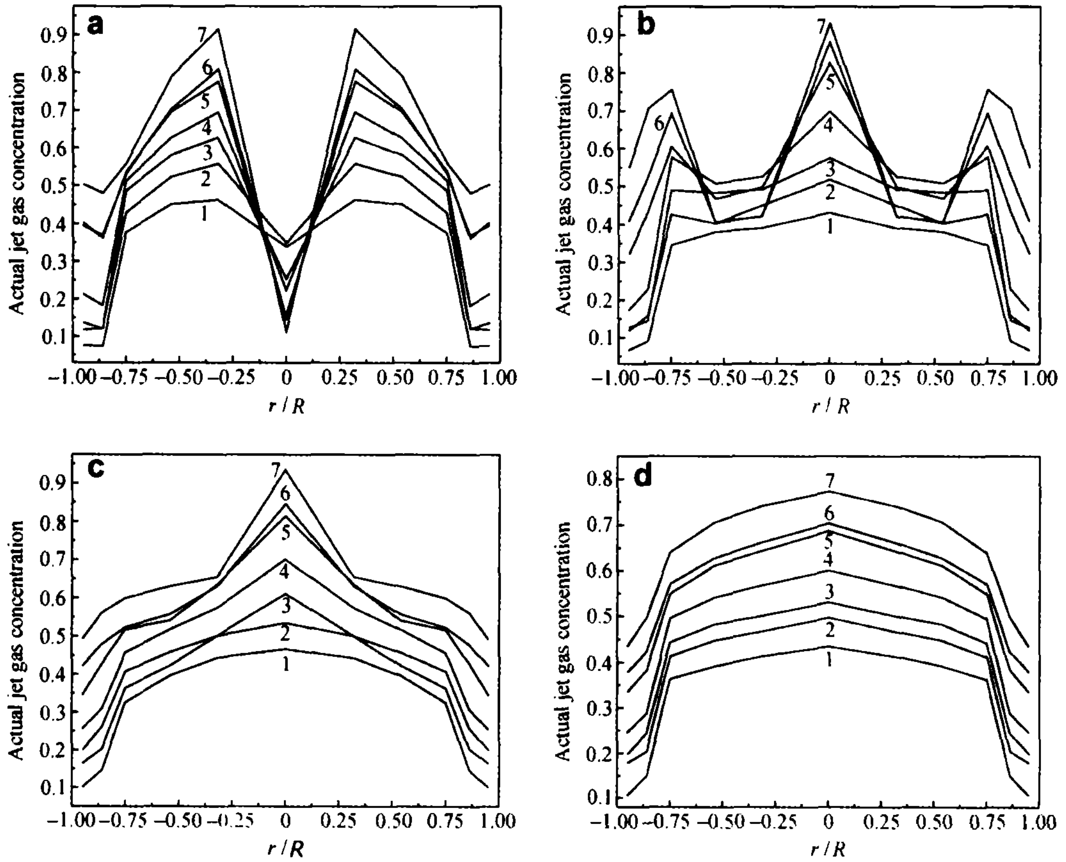

Fig. 7. Radial profiles of jet gas concentration at different values of M_j/M_r. Curves 1–7 represent jet gas concentration at $M_j/M_r = 0.29$, 0.54, 0.66, 1.05, 2.15, 2.37, and 4.21, respectively. (a) $H = 0.375$ m, (b) $H = 0.675$ m, (c) $H = 1.075$ m, (d) $H = 1.375$ m.

0.675 and 1.075–1.375 m, respectively, when the momentum ratio is greater than 0.54.

4. Conclusions

A new method has been proposed to investigate the jet gas actual concentration by using the hydrogen tracer technique. The maximum relative error between the calculated and measured jet gas volume flux is 4.2% and the average error is about 2.6%, which suggests that this method can precisely calculate the actual concentration of jet gas in a FCC riser.

Four types of the jet gas concentration profiles are found to represent four different mixing behaviors between jet gas and pre-lift gas. The distinct M-shaped profile stands for very weak mixing, the indistinct M-shaped profile for medium mixing, the sharp profile for strong mixing, and the parabolic profile for full mixing.

The effects of jet gas velocity and pre-lift gas velocity on the mixing characteristics between jet gas and pre-lift gas are investigated in the feed injection zone of the riser. The heights for regions of initial and full mixing decrease when reducing the jet gas velocity or increasing the pre-lift gas velocity.

A momentum ratio has been introduced to describe the effects of the physical properties of gas and solid, operating conditions, and equipment configuration on the jet gas concentration distribution. Experimental results have shown that the heights for regions of initial and full mixing decrease with the decreasing momentum ratio.

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