DOI 10.1007/s12182-014-0346-1

A handy method for estimating the particle concentration distribution in FCC risers using a gamma-ray transmission technique

Liu Xiaocheng, Wei Yaodong* and Song Jianfei

State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China

Abstract: A handy gamma-ray transmission method for estimating the particle concentration distribution in a fluid catalytic cracking (FCC) riser is proposed. The method is based on an empirical correlation $\varepsilon(r)=\overline{\varepsilon}^{(0.191+\phi^{2.5}+3\phi^{11})}$, which has only one unknown parameter $\overline{\varepsilon}$, hence only one single-beam experimental result is enough to estimate the particle concentration distribution in the riser. In order to verify the feasibility of this method, the particle concentrations of three cross-sections of the laboratory riser were measured and the distribution profiles were compared with those reported in the literature. Furthermore, by comparing other gamma-ray function methods applied in the measurement of risers, this method has distinct advantages, such as the device is simple and has no moving parts, the measurement is rapid, and the safety is high because only one gamma-ray beam is used. Therefore, the method has promising applications in estimating particle concentrations or monitoring operation conditions of risers.

Key words: Gamma-ray, riser, FCC catalyst, concentration measurement

1 Introduction

The riser is an important reactor in a fluid catalytic cracking (FCC) unit. The state of the gas-solid two-phase mixture in the riser can be normally described by particle concentration distribution, which is characterized by a lower dense-phase region and an upper dilute-phase region along the riser height, together with a lean-core region and a dense-annulus region over the lateral riser cross-section (Xu et al, 1999; 2004). The particle concentration distribution in the riser can directly affect the quality of the cracking product (Wolschlag and Couch, 2010). Thus, various methods have been adopted to measure the particle concentration distribution in the riser, but they have some shortages. The differential pressure method (Lin et al, 2005) can only be used to estimate the axial particle concentration distribution in the riser. By the probe method (such as the isokinetic sampling method, Han et al, 2012; and the optical fiber method, Liu et al, 2007; Huang et al, 2002) one can just measure one concentration point each time, interfering with the flow field to a certain extent. The most competitive methods for measuring particle concentration are the non-intrusive methods (Dantas et al, 2006). These include; radioactive materials must be added to solid particles in the radioactive tracer method (Wolschlag and Couch, 2010); sensors used in the electrical capacitance tomography method (ECT) (Wang et al, 2012) are mounted only outside a non-conducting pipe (Soleimani et al, 2007); good visual accessibility of the riser shell is required for particle imaging velocimetry (PIV) (He et al, 2009); in the X-ray method (Deng et al, 2002), a complicated device is need for radiation generation and measurement. They are not suitable for opaque industrial metal risers. The gamma-ray transmission technique (Dantas et al, 2013; Bao et al, 1995) can avoid the above-mentioned disadvantages to some extent, but radiological safety must be given considerable attention.

The traditional concentration imaging algorithm has poor applicability in industrial gamma-ray imaging, because it requires a large amount of data measured using a sophisticated scanner (Dantas et al, 2013; 2008a; Vasconcelos et al, 2011). The simplified concentration imaging algorithm, relying on a concentration distribution function, has been used in the concentration measurement of the riser, for example, the radial time-averaged concentration, the cross-section concentration, and the relationship between path chord length and radial concentration are assumed as a function by Tortora et al (2006), Bartholomew and Casagrande (1957) and Dantas et al (2006; 2008b), respectively. These methods have greatly improved the practicability of the gamma-ray transmission technique, because they can estimate the particle concentration distribution in the riser with few measurements (Dantas et al, 2013). However, in these methods, moving parts, including the detector array which is rotating around the riser, are necessary, hence they are complicated and required a large radiation safety protection area.

---

*Corresponding author. email: weiyd@cup.edu.cn

Received October 9, 2013

In this work, a handy method for estimating particle concentration distribution in the riser by using a gamma-ray transmission technique is proposed. It is based on a correlation for the particle concentration distribution in the riser (Zhang et al, 1991), and can predict the particle concentration distribution by means of only one measurement by a single gamma-ray beam. This method may be more suitable for predicting the particle concentration distribution in the riser.

2 Principle and method

2.1 Principle

The attenuation of a monoenergetic ray beam passing through a homogeneous absorbing medium follows the Lambert-Beer law:

$$I = I_0 e^{-\mu_m \rho L} \tag{1}$$

where I and I_0 respectively represent the intensity of the incident and emerging radiation beams. μ_m represents the mass attenuation coefficient; ρ is the medium density and L is the length along the path between source and detector. In operation, gas phase and solid phase flow in the riser, Eq. (1) can be expressed as:

$$I_f = I_0 e^{(\mu_v \rho_v L_v + \mu_p \rho_p L_p + \mu_g \rho_g L_g)} \tag{2}$$

where subscript v, p, g mean wall of riser, solid phase and gas phase, respectively. The portion of gamma-ray absorption in air can be neglected without appreciable error.

Commonly, gamma-ray intensity I can be expressed as photon count value N in unit interval. When a riser is measured in operating and non-operating status, and the photon count values are denoted as N_f and N_e, respectively. Then the average particle concentration ρ_{av} along the gamma-ray path can be derived from Eq. (2) as follows:

$$\rho_{av} = \frac{1}{\mu_m L} \ln \frac{N_e}{N_f} \tag{3}$$

where μ_m is the mass adsorption coefficient of particles available from prior calibration.

2.2 Function model

The particle concentration distribution in risers was reported to be mainly correlated with cross-sectional average voidage and radial position in previous research (Xu et al, 1999; 2004, Zhang et al, 1991, Werther, 1993, Wirth and Seiter, 1991, Rhodes et al, 1992). Zhang et al (1991) measured particle concentration distribution in a riser with an optical-fiber probe, under the assumption that concentration field was axially symmetric, and gave the voidage distribution function as follows:

$$\varepsilon(r) = \bar{\varepsilon}^{(0.191+\phi^{2.5}+3\phi^{11})} \tag{4}$$

where ϕ is the dimensionless radial position, $\phi = r/R$. $\bar{\varepsilon}$ is the cross-sectional average voidage. The correlation Eq. (4) is an empirical equation on the basis of the experimental data, and it had been used for predicting particle concentration distribution in the riser by Xu et al (2004) when $\bar{\varepsilon} > 0.75$. Its estimated error is 3% (Kwauk and Li, 2007). In Eq. (4), $\bar{\varepsilon}$ is the only unknown parameter and it can be solved by means of one experimental measurement ρ_{av}. Because the particle concentration distribution in riser is close to axial symmetry, the empirical function Eq. (4) can be used to predict the concentration distribution profiles. The beam passing through the cross-section center of the riser is selected to calculate the parameter $\bar{\varepsilon}$ for Eq. (4), and can give information on the whole cross-section voidage.

Eq (4) is a radial voidage distribution function. The average particle concentration ρ_{av} along the path is as follows:

$$\rho_{av} = \frac{\int_0^R [1-\varepsilon(r)]\rho_p \mathrm{d}r}{R} \tag{5}$$

where ρ_p is the particle concentration. Substituting Eq. (4) into Eq. (5) gives:

$$\rho_{av} = \frac{\int_0^R [1-\bar{\varepsilon}^{(0.191+\phi^{2.5}+3\phi^{11})}]\rho_s \mathrm{d}r}{R} \tag{6}$$

Eq (6) is the function relationship between ρ_{av} and $\bar{\varepsilon}$. In this work R is 0.04 m and ρ_p is 1,370 kg·m^{-3}, so a significant linear relation between cross-sectional average voidage ($\bar{\varepsilon}$) and average particle concentration (ρ_{av}) was obtained according to Eq. (6), as shown in Fig. 1. Therefore, $\bar{\varepsilon}$ can be calculated from the average particle concentration ρ_{av}.

Simplifying Eq. (6), and obtains:

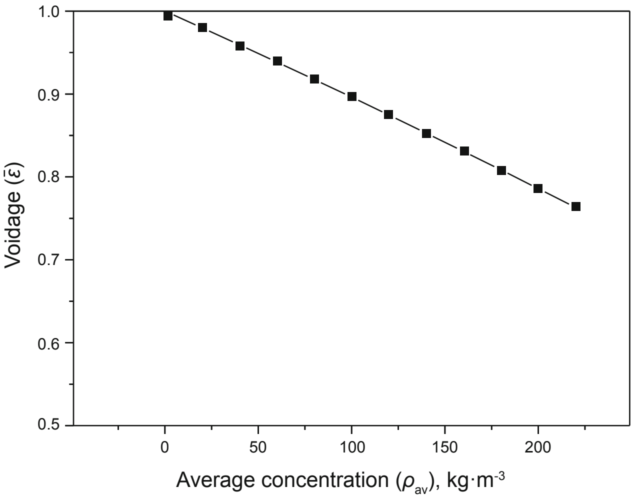

Fig. 1 The functional relationship between ρ_{av} and $\bar{\varepsilon}$

$$\int_0^R \bar{\varepsilon}^{[0.191+(\frac{r}{R})^{2.5}+3(\frac{r}{R})^{11}]} \mathrm{d}r = R - \frac{\rho_{av} R}{\rho_s} \tag{7}$$

where ρ_{av} can be acquired from Eq. (3) based on the experimental data, then $\bar{\varepsilon}$ can be solved by Eq. (7). Finally, the particle concentration distribution in the riser can be calculated as follows:

$$\rho(r)=[1-\varepsilon(r)]\rho_{\mathrm{s}}=\{1-\bar{\varepsilon}^{[0.191+(\frac{r}{R})^{2.5}+3(\frac{r}{R})^{11}]}\} \tag{8}$$

which relates the particle concentration at a radial position r to the inner radius R of the riser and cross-sectional average voidage $\bar{\varepsilon}$.

3 Experimental procedure

The gamma-ray test system used in this work is a GTS2005 gamma-ray tester, which is developed by the China University of Petroleum (Beijing), and mainly composed of a ^{137}Cs gamma-ray source and a NaI scintillation detector. The activity of gamma-ray source was 1.9 GBq.

The experimental setup used in this work was a small plexiglass circulating fluidized bed system (Fig. 2), in which the internal gas-solid two-phase flow state can be observed. The diameter and height of the riser were 80 mm and 4.2 m, respectively. Three cross-sections, H=1.5 m, 3.39 m and 3.92 m, were designed for measurement along the axial direction of the riser. In operation, the gas flow rate was measured with a flowmeter. A butterfly valve in inclined tube was used to control the particle circulation rate. In addition, the storage tank and the butterfly valve were set in the dipleg of the cyclone, and they can be used for measuring particle circulation rate.

The particles used in the experiment were FCC equilibrium catalyst, with a particle density of 1,370 kg·m^{-3} and a median particle size of 65 μm. The gas medium was air at normal temperature.

The ^{137}Cs gamma-ray source and NaI detector were installed in a steel support that maintained the source-riser-detector geometry. The support fixed the source-detector distance and the position of the axial direction of the riser, and kept the gamma-ray beam passing through the center of the riser. After a period of steady operation at a given gas flow rate and particle circulation rate, the particle concentration in the specified cross-section of the riser was measured by using one gamma-ray beam. In order to reduce the effects of unstable factors on results, the measurement at each specified section was repeated 60 times and the time for each measurement was 5 s. The average photon count value N_{f} (for a riser in operating status) or N_{e} (for a riser in non-operating status) was then obtained.

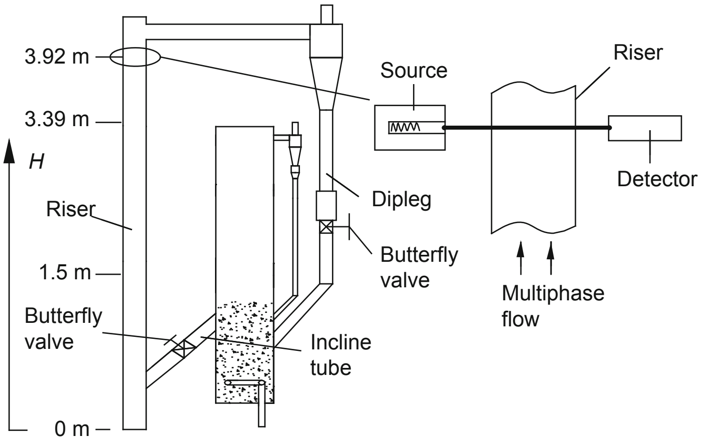

Fig. 2 Experimental setup

4 Results and discussion

4.1 Concentration distribution in the riser

Experiments were carried out at a superficial gas velocity of 10.71 m·s^{-1} and particle circulation rates G_{s} of 19.6 kg·m^{-2}·s^{-1} and 16.4 kg·m^{-2}·s^{-1}. The average particle concentration ρ_{av} can be calculated by Eq. (3) based on the photon count values N_{f} and N_{e}. The cross-sectional average voidage $\bar{\varepsilon}$ was obtained by Eq. (7). The results are summarized in Table 1.

Table 1 Experimental results

G_{s}, kg·m^{-2}·s^{-1}	H, m	ρ_{av}, kg·m^{-3}	$1-\bar{\varepsilon}$
19.6	1.50	2.35	0.0024
	3.39	2.13	0.0022
	3.92	2.06	0.0021
16.4	1.50	2.09	0.0021
	3.39	1.92	0.0020
	3.92	1.76	0.0018

Substituting the value of $\bar{\varepsilon}$ in Table 1 into Eq. (8), the radial particle concentration distributions in three cross sections of the riser were obtained. The profiles, as shown in Fig. 3, were characterized by lean concentration at the core and dense concentration at the annulus of the riser, which was typically described by a core-annulus model, also the characteristics of fast fluidized bed. The dividing point between the core and the annulus was at the radial position of about ϕ=0.7.

The profiles indicate that the particle concentration had significant radial non-uniformity. The radial particle concentration increased slightly with increasing radial position when the radial position ϕ was less than 0.7, however the radial particle concentration increased significantly with increasing radial position when the radial position ϕ was larger than 0.7. This concentration distribution behavior is attributed to the decrease of the gas velocity near the wall, which resulted in the accumulating and clustering of particles. Meanwhile along the axial direction, the ρ_{av} value slightly decreased with increasing axial position H (see Fig. 3), while

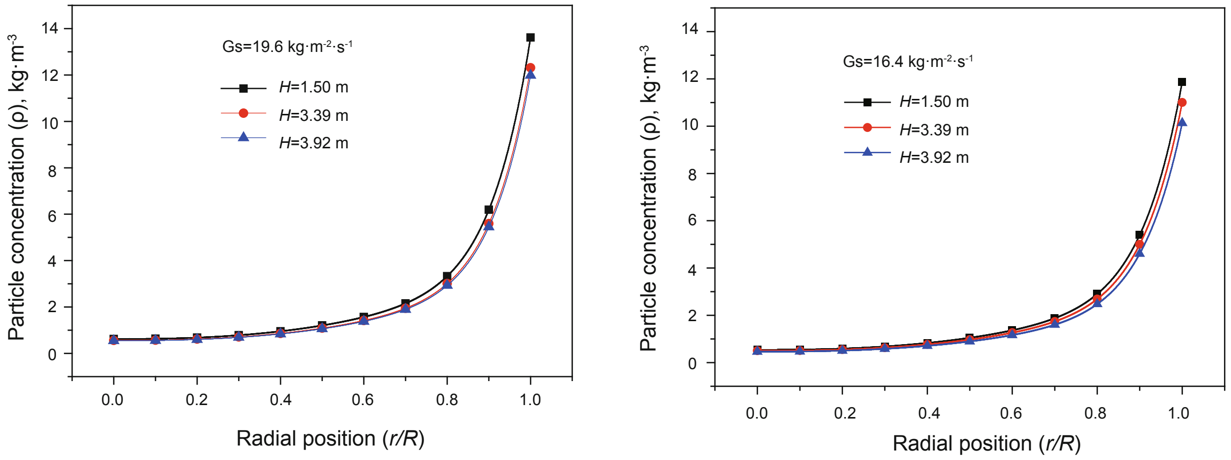

Fig. 3 Radial particle concentration distribution profiles in the riser

the cross-sectional average voidage $\bar{\varepsilon}$ increased gently (see Table 1).

The voidage at radial position can be calculated with Eq. (4). Fig. 4 shows the comparison of the cross-sectional voidage in this work (with the average cross-sectional voidage of $\bar{\varepsilon}$=0.9976 at the measuring position of H=1.5 m when the riser height of H=4.25 m) and that reported by Xu et al (1999) (with the average cross-sectional voidage of $\bar{\varepsilon}$=0.993 at the measuring position of H=3 m when the riser height of H=11 m). The both profiles were similar, except for the voidage showing some disparity when the radial position ϕ close to 1, that is, the predicted cross-sectional voidage in this work was little larger than that by Xu et al (1999) due to the great difference of $\bar{\varepsilon}$. Therefore, the results of this work can be considered credible.

4.2 Comparison with other function methods

Many function methods for measuring particle concentration distribution in the riser have been reported (see Table 2). They are different mainly in functional form. The comparison of the method proposed in this work with those in literature is given in Table 2.

Except for the method reported by Bartholomew et al (1957) (with an error of about 26%), the other methods in Table 2 have an error of 0.5%-3.0%. The error of this work was about 3%, which resulted from the experimental errors, mainly the alignment between the source and the detector.

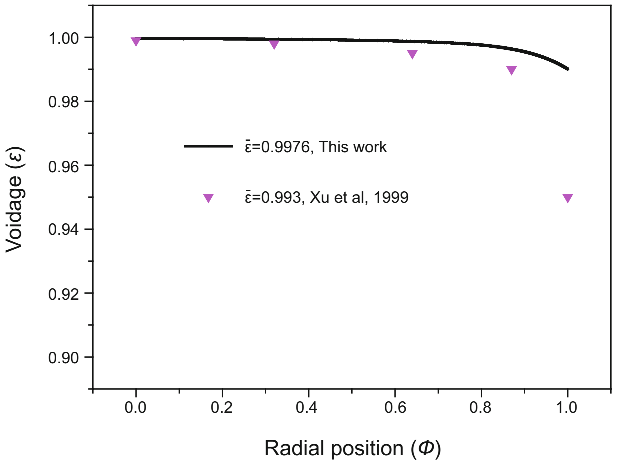

Fig. 4 Comparison of cross-sectional voidage between this work and Xu et al, 1999

Table 2 Comparison of the function methods

Authors	Function	Data number	Detector array	Time	Moving parts	Error		
						Point	Function	Total
Dantas et al (2006)	$\rho_{\mathrm{m}}=\dfrac{1}{\mu_{\mathrm{m}}c_i}\ln\dfrac{\int_{r_0}^{r_i} I_{\mathrm{v}}\mathrm{d}r}{\int_{r_0}^{r_i} I_{\mathrm{f}}\mathrm{d}r}$	18	No	–	Yes	0.5%	3%	–
Tortora et al (2006)	$\rho(r)=a_1+a_2(r/R)^2+a_3(r/R)^4$	8	Yes	6 min	Yes	–	–	<1%
Bartholomew et al (1957)	$\rho(x,y)=a_1+a_2x+a_3y\cdots$	18	Yes	1 hour	Yes	26%	–	–
This work	$\rho(r)=\{1-\bar{\varepsilon}^{[0.191+(\frac{r}{R})^{2.5}+3(\frac{r}{R})^{11}]}\}$	1	No	5 min	No	3%	3%	–

The uncertainty error of 3% in this work can be improved by prolonging the measurement time or increasing the number of measurements. It can be seen that the method in this work has many advantages, especially in the number of measurements to be used and the lack of any moving parts. Therefore, the measurement process is faster than other methods when one source and one detector are used, and is also more convenient and safer.

5 Conclusions

A method has been proposed to estimate the particle concentration distribution in the riser with a simple and practical gamma-ray transmission technique. By means of an empirical concentration correlation function $\varepsilon(r)=\bar{\varepsilon}^{(0.191+\phi^{2.5}+3\phi^{11})}$, the particle concentration distribution profile can be estimated using 60 measurements from one gamma-ray beam. This method has been shown to be feasible experimentally and using comparisons with the previous literature. The method can predict the main features of gas-solids flow in the riser. So it may have good prospects for handy estimation of the particle concentration in risers.

Nomenclatures

I	Intensity of the incident gamma-ray beam
I_0	Intensity of transmit gamma-ray beam
L	Medium thickness, m
N	The count intensity of gamma-ray, s^{-1}
r	Radial position, m
R	Radius of riser, m
c_i	Chord length, m (i=1, 2, 3, ···)
$a_1, a_2, a_3\dots$	Coefficients in density equation
r_i	Scan point (i=0, 1, 2, ···)
Greek letters	
μ_m	Mass absorption coefficient
ρ	Density of homogeneous material, kg·m^{-3}
ρ_aw	Average concentration, kg·m^{-3}
ε	Voidage
ϕ	Dimensionless radial position, $\phi=r/R$
$\bar{\varepsilon}$	Cross-sectional average voidage
ρ_m	Density, kg·m^{-3}
Subscripts	
v	Riser wall
p	Solid phase
g	Gas phase
f	Operated riser
e	Empty riser

Acknowledgements

The authors acknowledge the financial support of the China National High Technology Research and Development Program (863 Program) (Grant no. 2011AA060802) and the National Natural Science Foundation of China (Grant no. 21176250).

References

Bao X J, He K AN, Liu Y SH, et al. Insight into distillation/absorption columns and FCC risers using gamma scanning technique. Chinese Journal of Chemical Engineering. 1995. 3(3): 171-179

Bartholomew R N and Casagrande R M. Measuring solids concentration in fluidized systems by gamma-ray absorption. Industrial & Engineering Chemistry. 1957. 49(3): 428-431

Dantas C C, Dos Santos V A, Melo A C B A, et al. Precise gamma ray measurement of the radial distribution of a cracking catalyst at diluted concentrations in a glass riser. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2006. 251(1): 201-208

Dantas C C, Melo S B, dos Santos V A, et al. A study of uncertainty evaluation in transmission measurement in gamma ray tomography, 12th IMEKO TC1 & TC7 Joint Symposium on Man Science & Measurement, France. 2008a. 3-5

Dantas C C, Melo S B, Oliveira E F, et al. Measurement of density distribution of a cracking catalyst in experimental riser with a sampling procedure for gamma ray tomography. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2008b. 266(5): 841-848

Dantas C C, Moura A E, Rolim T L, et al. Data evaluation and visibility in single beam scanner of gamma ray tomography. World Journal of Nuclear Science and Technology. 2013. 3: 22-27

Deng R SH, Wei F, Liu T F, et al. Radial behavior in riser and downer during the FCC process. Chemical Engineering and Processing: Process Intensification. 2002. 41(3): 259-266

Han H B, Wang J J, Yuan C G, et al. Experimental study on back-mixing of particles in PSC-type guide vane cyclone tube. Petro-Chemical Equipment. 2012. 41(02): 1-7 (in Chinese)

He Y, Deen N, Annaland M v S, et al. Gas− solid turbulent flow in a circulating fluidized bed riser: experimental and numerical study of monodisperse particle systems. Industrial & Engineering Chemistry Research. 2009. 48(17): 8091-8097

Huang W X, Qi X B, Pan Y L, et al. Local solid-particle concentration and flow development in a long CFB riser. Journal of Chemical Engineering of Chinese Universities. 2002. 16(6): 626-631 (in Chinese)

Kwauk M and Li H Z. Handbook of Fluidization. Beijing: Chemical Industry Press. 2007 (in Chinese)

Lin H B, Huang W X, Qi X B, et al. Axial distributions of averaged solids holdups for coarse particles in CFB riser. Journal of Chemical Engineering of Chinese Universities. 2005. 19(3): 327-331 (in Chinese)

Liu X CH, Lu C X and Shi M X. Post-riser regeneration technology in FCC unit. Petroleum Science. 2007. 4(2): 91-96

Rhodes M, Zhou S and Benkreira H. Flow of dilute gas–particle suspensions. AIChE journal. 1992. 38(12): 1913-1915

Soleimani M, Vauhkonen M, Yang W, et al. Dynamic imaging in electrical capacitance tomography and electromagnetic induction tomography using a Kalman filter. Measurement Science and Technology. 2007. 18(11): 3287-3294

Tortora P R, Ceccio S L, O'Hern T J, et al. Quantitative measurement of solids distribution in gas–solid riser flows using electrical impedance tomography and gamma densitometry tomography. International Journal of Multiphase Flow. 2006. 32(8): 972-995

Vasconcelos G, Melo S, Dantas C, et al. A particle system approach to industrial tomographic reconstruction. Measurement Science and Technology. 2011. 22(10): 104003

Wang Z P, Liu Q, Cao L P, et al. Concentration of dense gas-solids flow based on electrical capacitance tomography. Journal of Chongqing University of Technology (Natural Science). 2012. 26(03): 68-74 (in Chinese)

Werther J. Fluid mechanics of large-scale CFB units. Circulating Fluidized Bed Technology IV. 1993: 1-4

Wirth K and Seiter M. Solids concentration and solids velocity in the wall region of circulating fluidized beds. Proceedings of the International Conference on Fluidized Bed Combustion, Montreal, Quebec (Canada), 1991

Wolschlag L and Couch K. Upgrade FFC performance—Part 1: New ceramic feed distributor offers ultimate erosion protection. Hydrocarbon Processing. 2010. 89(9): 57-65

Xu G W, Sun G G and Gao S Q. Estimating radial voidage profiles for all fluidization regimes in circulating fluidized bed risers. Powder Technology. 2004. 139(2): 186-192

Xu G W, Sun G G, Nomura K, et al. Two distinctive variational regions of radial particle concentration profiles in circulating fluidized bed risers. Powder Technology. 1999. 101(1): 91-100

Zhang W, Tung Y and Johnsson F. Radial voidage profiles in fast fluidized beds of different diameters. Chemical Engineering Science. 1991. 46(12): 3045-3052

(Edited by Zhu Xiuqin)