LATERAL AND AXIAL MIXING OF THE DISPERSED PARTICLES IN CFB

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The lateral and axial mixing of dispersed particles in a circulating fluidized bed were measured by using the phosphor tracer technique. The measured residence time distribution was satisfactorily described by a proposed two dimensional plug flow dispersion flow. Compared with that in the cocurrent downflow circulating fluidized bed (CDCFB), the dispersion Peclet numbers for lateral and axial mixing of dispersed particles is about the same value with that in CDCFB (downer). Correlations of the Peclet numbers under the operating conditions are presented.

Intoroduction

Intvertigations of axial solids mixing in circulating fluidized bed have proved the degree of mixing to be very high^{(1)~(5)}. The structure of the riser is characterized by the dilute phase fast moving particles in the core region and a more dense phase downward moving pasticles in the annulus region, which have been reported by many investigators. Information on the lateral and longitudinal mixing of solids in gas-solid risers is of very important for its performance as a reactor. However little research has been done towards lateral solids in the riser of CFB. As a result this aspect of riser is less well understood.

The solids mixing study was poineered by Zoonen¹⁾ in a 50mm riser. The lateral solids dispersion coefficient was found to be $30 \pm 10 \text{ cm}^2/\text{s}$ and kept constant with operating conditions. Avidan and Yerushalmi²⁾ measured solids mixing using a ferro-magnetic tracer and an induction bridge detector in a 0.152 m diameter riser and applied a one-dimensional dispersion to obtain measures of solids dispersion coefficient. Ambler *et al.*³⁾ found bimodal distribution of RTD in their experiments using a radioactive solids tracer. Bader *et al.*⁴⁾ and Rhodes *et al.*⁵⁾ used sodium chloride as the tracer that was detected by dissolving in water and by measuring electrical conductivity. Their single-peak residence time distributions indicated a high degree of solids backmixing in the wall region and a substantial transfer of solids between riser core and wall regions. However, these studies provide very limited number of data, insufficient for a proper analysis.

To study the solid mixing an experimental technique is required which has a fast response, and can measure the local tracer concentration without disturbing the system. Also, the technique must be such that tracer does not accumulate in the bed. In this way, experiments can be

repeated a number of times and meaningful average values obtained. The main objective of the present work was the determination of the lateral and axial solids dispersion in the core region of riser. With this in mind, an innovative phosphor tracer technique is developed to measure the solids RTD at small distances above the injection point in the riser. A two dimensional solids mixing model is proposed to characterize the solids mixing behavior.

1. Solids Mixing Experiments

1.1 Experimental apparatus and material

The circulating fluidized bed test rig used in the experiments is shown schematically in **Fig. 1**. The riser tube is 140 mm in inner diameter and 12 m in height. The top of the riser is connected to a primary cyclone. The gas and solids are redistributed in a mutlitube distributor and move down in the cocurrent downflow tube, called downer, which has the same diameter with riser. The main parts of the apparatus are made of Plexiglas and the inner wall of the riser tube is covered with cellophane tape to prevent the electrostatic charge. The superficial gas velocity is measured by rotameters. The solids circulating rate is measured by using three-way valve. Axial pressure gradients are taken from pressure taps distributed along the riser. The operating gas velocity and solid circulating rate are in the range of 2.67 to 7.84 m/s and 3 to 160 kg/m²s respectively. Further details of the apparatus have been reported elsewhere⁽⁶⁾. Experiments were carried out at ambient temperature and pressure with air. A special kind of alumina with a mean diameter of 54 μm and particle density of 1710 kg/m³ is used as circulating solids. The alumina particles contain small amount of very fine phosphor particles(less than 10 μm) for the solids mixing study.

1.2 The phosphors tracer technique

Phosphor material has a unique characteristic: once

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Fig. 1 Diagram of experimental apparatus

Fig. 2 Diagram of phosphor tracer method

it is excited by a light source, it will emit light immediately and the light emission can last a few minutes, the strength of which will decay with time. It is an ideal material as solids tracer. This phosphor solids tracer has a number of advantages:

- Easy and immediate tracer injection by a light impulse.
- Easy on line detection of tracer by a light detector.
- Tracer is identical to the rest of the bed particles.
- No tracer accumulation in the bed; within a few minutes after injection, the tracers will decay out and will become indistinguishable from the rest of the bed.

Fig. 3 Decay curve of phosphor emissive light

Each phosphor tracer experiment consisted of two parts: tracer injection, and tracer detection. Fig. 2 shows the diagram of this method.

An electric flash tube (4 mm in ID) was fixed in the axis of the riser, 2.5 m above the recirculating solids inlet, as shown in Fig.2. The fluidization was started by regulating the flow rate to the desired value, allowing bed material to fluidize for a time to reach a steady-state.

Under steady operating conditions, a strong light impulse was suddenly produced by the flash tube, at time zero, to excite the phosphor particles surrounding the flash tube. The excited phosphor particles, i.e., tracers, gave out the emissive light immediately. The tracer injection process was thus completed. When the tracer passed by the detector, the emissive light signals were detected by a photomultiplier and collected by a computer data acquisition system as a function with time. In order to inject the tracer as a point source, a cylinder ring made of thin metal sheet with 40 mm in ID and 50 mm in length were coaxial installed to surround the flash. In this way, the tracer could be injected in less than 3 milliseconds just as a delta function injection, without disturbing the flow pattern.

Three axial locations, 0.38, 0.8, 1.4 m, downstream the injection point in the riser and one axial location, 0.40 m, downstream the injection point in the downer were chosen to measure RTD in different lateral positions. The light detector was a 10mm in ID tube connected with a photomultiplier light detector. Five lateral positions, $r/R = 0.0, 0.29, 0.57, 0.86$ and 1.0 , were chosen to measure the local solids concentration.

As the strength of emissive light is proportional to the tracer concentration, by subtracting the light strength decay from the emissive light, the tracer concentration can be obtained. This light tagging permits repeated tests to be

carried out in rapid succession and it provides a simple method for measuring the local, transient tracer concentration while the solids are undergoing a rapid movement.

2. Data Processing

The strength of emissive light decays with time. The decay process was measured as a function with time, as shown in **Fig. 3**. Following power function obtained by nonlinear regression analysis could fit this decay curve very well:

$$I_1(t) = At^{-1.09} \quad (1)$$

Where A is a constant that is related to the property of phosphor particles and the exciting light.

Thus the tracer concentration $C(t)$ in the riser can be expressed as a ratio of the detected emissive light strength $I(t)$ with the phosphor decay curve $I_1(t)$ as follows:

$$C(t) = \frac{I(t)}{I_1(t)} = \frac{I(t)t^{1.09}}{A} \quad (2)$$

For every RTD curve, ten of experimental RTD measurements were made to get the meaningful average. More than 30 sets of solids mixing measurements were conducted with the CFB apparatus under various operating conditions.

3. Modeling

Particles exist in a CFB mainly in two forms: the dispersed particles and clusters. Backmixing measurements and axial dispersion studies show that axial solids mixing in riser occurs mainly by the aggregation of solids, i.e. clusters. Hydrodynamics studies indicate that the characteristics of the annular region are somehow different from those of the core, where solids concentration is low and particles mainly exist in the form of dispersed particles and the solids mixing mechanism is dominated by the lateral and axial dispersion. So the solids mixing model for the riser should be divided into two parts, the mixing of dispersed particles and clusters, and physically, their boundary should correspond to the hydrodynamic boundary of core-annulus structure. Unfortunately, no clear definition exists to determine unambiguously its boundary up to date.

With this in mind, the boundary of our model, mainly concerned with the solids mixing of dispersed particles, was made to cover all the riser cross-section. We investigated the possibility of describing the mixing phenomena using two-dimensional plug-flow dispersion model. Make following model assumptions:

- Uniform solids velocity profile.
- Bulk flow only in the axial direction.
- Dispersion coefficients, both axial and lateral, are independent of position.
- Axisymmetric concentration distribution

The solids mixing of dispersed particles in riser is

Fig. 4 Typical RTD curves at different lateral positions

characterized by a coefficient of axial dispersion D_a and a coefficient of lateral dispersion D_r . Provided the tracers is injected as a δ -function in the origin and the tracer concentration profiles were evaluated using the dispersed plug flow model, diffusion and convection under conditions of uniform flow may then described by:

$$D_a \frac{\partial^2 c}{\partial x^2} + \frac{D_r}{r} \frac{\partial}{\partial r} \left(r \frac{\partial c}{\partial r} \right) - U_s \frac{\partial c}{\partial x} = \frac{\partial c}{\partial t} \quad (3)$$

with boundary conditions:

$$r = R, \frac{\partial c}{\partial r} = 0; \quad r = 0, \frac{\partial c}{\partial r} = 0, \quad x = -\infty, c = 0; \\ c(t, x, r) = c_0 \cdot \delta(t, x, r)$$

The distance L between the point of tracer injection and the measuring plane is positive in the direction of flow. The analytical solution of the equation is given as follows:

$$\frac{C}{C_0} = \frac{e^{-\varphi \xi}}{2\pi\sqrt{\pi}\theta} \sum_{n=0}^{\infty} \frac{J_0(\beta_n \rho)}{J_0^2(\beta_n)} \left[-\frac{\xi^2}{4\theta} - (\varphi^2 + \beta_n^2)\theta \right] \quad (4)$$

Where $\rho = \frac{r}{R}$, $\xi = \frac{z\sqrt{D_r}}{R\sqrt{D_a}}$, $\varphi = \frac{U_s R}{2\sqrt{D_a D_r}}$, $\theta = \frac{D_r t}{R^2}$,

$Pe_a = \frac{U_s L}{D_a}$, $Pe_r = \frac{2U_s R}{D_r}$ β_n is the n -th positive root for which the Bessel function $J_1(\beta_n)$ is zero.

4. Results and Discuss

4.1 The Characteristics of RTD in the riser

The experimental RTD curves at different lateral positions are shown in **Fig. 4**. The RTD curves in the riser (Fig.4a) consist of a series of single peak curves, indicating that the solids mixing mechanism in riser is dominated by dispersion which is similar with that of CDCFB reported elsewhere⁽⁶⁾.

Since the tracers in the injection area are mainly in the form of dispersed particles and the RTD curves are measured at small distances above the injection point, the lateral and axial dispersion can be considered as the main mixing mechanism. Because of the lateral solids dispersion, the peak height of RTD curves measured in the center

Fig. 5 Effect of gas velocity on lateral and axial Peclet numbers in the riser and downer

Fig. 6 Effect of solids fraction on lateral Peclet number in the riser and downer

larger than that near the wall and the smaller the distance between the injection point and the measuring plane, the larger the difference in the higher of peak between local RTD curves in the axis and at the wall. If the distance above the injection point is more than 0.8 m under certain operating conditions, the measured RTD curves at different lateral positions are the same, as shown in Fig.4b. That is to say the solids lateral mixing is to the extent that under these operating conditions and measuring distance the tracer concentration along lateral direction are the same. In other words, the detecting efficiencies of solids tracer under the operating conditions are unchanged with varying in local bed voidage along lateral direction of the riser.

The mixing parameters Pe_r and Pe_a are determined by fitting the experimental results of tracer concentration versus time with the profiles at particular values of r/R , as shown in Fig. 4a. A two-dimensional non-linear least-squares regression technique is used. A sensitivity analysis demonstrates that the Pe_a values in Eq. (4) are sensitive to the shape of RTD curves, Pe_r values are sensitive to the peak height of RTD curves in different radii. In order to guarantee enough sensitivity for lateral dispersion coefficient measurement the distance between injection point and measuring plane is relatively small, the distance is 0.38 m for the riser and 0.4 m for the downer.

Fig. 7 Effect of gas velocity on lateral and axial Peclet numbers in the riser and downer

4.2 Comparison of model with experimental results

The comparison of the model prediction with the experimental data is also shown in Fig.4a.

The proposed model can describe the experimental RTD very well for riser, except in the wall region of the riser, indicating that the model assumption of solids mixing in the riser follows the behavior of dispersion mixing mechanism is correct. The scatter of experimental data from the model in the wall region of the riser may be caused by the existence of large clusters and down flows of solids which makes the mixing behavior different from that of the riser center.

Fig. 5 (a) plots the obtained model parameter Pe_r , the lateral solids mixing Peclet number, varies with the gas velocity in riser and downer. When the solids flux is kept constant, a weak decrease in Pe_r with increasing gas velocity in downer and Pe_r keeps constant with varying gas velocity in the riser. The Pe_r in the riser is larger than that of downer, showing less solids lateral mixing of dispersed particles. As shown in Fig.5 (b), increase gas velocity will increase the axial Peclet number of the riser, Pe_a . Pe_a keeps constant with gas velocity in the downer. The Pe_a in the riser is smaller than that of the downer at low gas velocity, and reaches the same value at high gas velocity. Since the solids in the downer exist in form of dispersed particles, the Pe_a both in the riser and the downer having about the same value indicates that the lateral and axial solids dispersion measured by this technique are only those of dispersed particles in the riser. Compared with the axial Peclet number reported by Avidan *et al.*²⁾ and Rhodes *et al.*⁵⁾ in risers, the Pe_a obtained in this paper is one magnitude of order larger than that of others, which is another evidence showing that the dispersion measured by using this method is the mixing of dispersed particles.

The second series of experiments is aimed at determining the effect of solids concentration on the lateral and axial solids dispersion Peclet number. Fig. 6 illustrates the effect of solids volume fraction on the Pe_r and Pe_a in riser and downer. Both lateral and axial Peclet numbers in the riser exhibit the trend of increasing with increase solids fraction, except that the axial solids Peclet number in the downer shows the opposite trend of decreasing with increase of solids fraction.

In spite of the little difference between the riser and the downer, both Pe_r and Pe_a almost have the same range of values over the experimental operation conditions. Keeping the same average bed density as calculated from the axial pressure profile in the riser constant, Peclet number is plotted against gas velocity in Fig. 7. Lateral and axial Peclet number decrease with solids volume fraction. Compared with the lateral solids dispersion coefficient reported by van Zoonen¹⁾, the coefficients obtained in this study have the same range of value with that of van Zoonen¹⁾, although the diameter of the two studies are quite different.

4.3 Correlations

The results shown in Figs 5, 6 and 7 indicate that the apparent Peclet numbers can be represented as a function of the bed voidage and gas phase Reynolds number. Correlations for both the lateral and axial Peclet numbers in the riser are obtained by regression all of the experimental data. These correlations can be expressed as follows:

$$Pe_r = 225.7 (1 - \varepsilon)^{0.29} Re^{0.3} \quad (5)$$

$$Pe_a = 71.86 (1 - \varepsilon)^{0.67} Re^{0.23} \quad (6)$$

Comparison of the correlations calculated ones with experimental ones show that both lateral and axial correlations fit the experimental Peclet numbers well, with average error of 10%.

Conclusion

The experimental results obtained from this investigation indicate that the two-dimensional plug flow dispersion model is a good model for the dispersion of dispersed solids of riser.

The lateral and axial Peclet number characterizing the mixing of dispersed particles are determined as function of the Reynolds number and bed voidage over the range of observed experimental conditions and compared the results with that of downer. Correlations of lateral and axial Peclet numbers are presented.

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Nomenclature

C	= relative concentration of the phosphors tracer,	[-]
C_0	= initial relative tracer concentration	[-]
D	= diameter of the riser	[m]
D_a	= axial solids dispersion coefficient	[m ² /s]
D_r	= lateral solids dispersion coefficient	[m ² /s]
G_s	= solids flux	[kg/m ² s]
L	= axial distance from the injector to the measuring plane	[m]
Pe_a	= Peclet number for the axial solids dispersion, LU_g/Da	[-]
Pe_r	= Peclet number for the lateral solids dispersion, DU_g/Dr	[-]
r	= lateral coordinate	[m]
R	= radius of the riser	[m]
Re	= gas phase Reynolds number, $DU_g \rho_g / \mu$	[-]
t	= residence time	[s]
U_g	= superficial gas velocity	[m/s]
U_s	= superficial solids velocity	[m/s]
z	= axial coordinate	[m]

Greek letter

ε	= average bed voidage	[-]
ξ	= dimensionless axial position, $\xi = \frac{x\sqrt{D_r}}{R\sqrt{D_a}}$	[-]
φ	= dimensionless dispersed fine particles velocity, $\varphi = \frac{U_s \cdot R}{2\sqrt{D_a D_r}}$	[-]
θ	= dimensionless time, $\theta = \frac{D_r \cdot t}{R^2}$	[-]
μ	= gas viscosity	[kg/m·s]
ρ	= reduced lateral position, $\rho = r/R$	[-]
ρ_g	= gas density,	[kg/m ³]
β_n	= the n-th positive root for the Bessel function $J_1(\beta_n) = 0$	[-]

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