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TWO-PHASE FLOW STRUCTURE IN A COLD MODEL GAS-SOLID AIRLIFT LOOP REACTOR

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ABSTRACT
Experiments have been conducted in a cold mode gas-solid airlift loop reactor. Transient solid holdup signals were registered by an optical fiber probe and statistically analyzed. Results show that probability density function curves of transient signals are bimodal distributions and can be mathematically simulated by coupling the log-normal distribution and Gaussion distribution. Mean solid holdup of the bubble phase ranges from 0.1 to 0.15, significantly affected by operating conditions and local two-phase flow in different regions.

INTRODUCTION
Contact of gas and solid particles plays a key role in determining the performance of the gas-solid fluidized bed reactors. Up to now, a thorough understanding on gas-particle contact has still not been achieved, because of lack of effective measurement techniques and complex flow structures of the bubble and emulsion phases. Studies on flow structure in gas-solid fluidized beds have been mostly limited to circulating fluidized beds (1) or freeboard of bubbling and turbulent fluidized beds (1,2), while those associated with the bubbling and turbulent fluidized bed have been rare.

There are probably three ways associated with gas-particles contact in a gas-solid fluidized bed, respectively occurring in bubbles and the emulsion, and on bubble's surfaces. The two-phase theory provides classical description of flow structure in the bubbling and turbulent fluidized bed (3). It assumes that all gas in excess of u_{mf} flows through the bed as bubbles and the bed consists of pure bubbles containing absolutely no particles and the emulsion of a constant voidage of ε_{mf}, signifying a gas-particle contact only occurring in the emulsion and on the bubble surfaces. The description of the two-phase theory may not always agree with experimental results, because it ignores particles dispersed in bubbles and agglomerates existing in the emulsion phase (4,5).

Many researchers found evidence of particles dispersed in bubbles (4, 5,6), which suggests a possible gas-solid contact inside bubbles. Particles inside bubbles may exist in two ways, namely dispersed particles and the agglomerates. It means that gas-solid contact may be significantly affected by mean solid holdup and standard deviation of solid holdup of the bubble phase. Cui *et al.* (4) statistically analyzed local transient signals registered by a cross-optical fiber probe. The probability density function (PDF) of voidage shows a bimodal curve which can be described by coupling two beta distributions and the two peaks respectively correspond to the bubble phase and the emulsion phase. The mean solid holdup of the bubble phase, $\bar{\varepsilon}_{sb}$, decreases from about 0.15 to 0.03 as superficial gas velocity u_g increases from

0.1 to 0.9 m/s, signifying a weakened gas-particle contact inside bubbles with gas velocity. While Lin *et al*. (5) found a different evolution that, with increasing superficial gas velocity, $\overline{\varepsilon}_{sb}$ firstly increases and reaches a maximum at u_g of about 2 m/s, and then decreases. The disagreement of results of Cui and Lin may arise from different ways to identify the bubble phase and the emulsion phase. The gas-particle contact happening in the emulsion is mainly related to the emulsion voidage. Cui *et al.* (4) found that, for FCC particles, gas in excess of u_c mainly enters and dilutes the emulsion phase rather than forming more bubbles and increasing the bubble phase fraction. While for sand particles, the excess gas mainly enters bubbles or voids and consequently increases the bubble phase fraction. This indicates a varying gas-particle contact with operating condition and physical property of the bed material. Mostoufi and Chaouki (7) found that particle velocity is lower than that of a single and isolated particle under same condition. By using a radioactive particle tracing technique, Mostoufi and Chaouki (8) measured particle behavior in a bubbling fluidized bed dealing with sand. It was found that tracer particles did not exhibit a Brownian-like motion, but moved upward and downward along straight lines, which signifies the existence of bubbles and agglomerates in the bed. They also estimated agglomerate diameters and found that the descending agglomerates are usually larger than that of ascending ones and the diameter of both agglomerates increases with the increase of superficial gas velocity.

The present paper proposed a novel gas-solid air-loop reactor (GSALR) dealing with fine Geldart A particles and operating in a new draft tube-lifted mode, with bubbling or turbulent bed upward flow in the draft tube in parallel with bubbling bed downward flow in the annulus. Transient bed density signals were measured and the two-phase flow structure was analyzed for different regions of the reactor.

EXPERIMENTAL APPARATUS

The experimental apparatus is shown schematically in Fig. 1. The draft tube-lifted GSALR column was made of Plexiglas, 286 mm in inner diameter and 4560 mm in height. A draft tube of 220 mm ID was coaxially mounted in the column. As the draft tube gas distributor, a perforated plate distributor of an open ratio of 0.8 % was used positioned at the bottom. A 256 mm ID ring distributor of an open ratio of 0.2% was mounted 30 mm below the bottom of annulus. 9 holes of diameter 3 mm were drilled at the bottom of ring at an angle of 60°. The gap height (distance from bottom of draft tube to perforated plate distributor) was 64 mm.

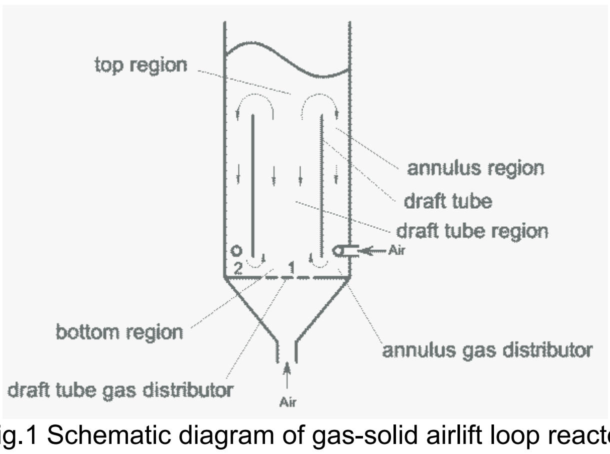


Fig.1 Schematic diagram of gas-solid airlift loop reactor

Different flows of air were introduced into the draft tube-lifted GSALR by the draft tube distributor and ring distributor. The bed material was FCC catalyst (ρ_s=1498 kg/m^3, ρ_b=862 kg/m^3), with an average diameter of 75 μm. All experiments were conducted at ambient pressure with a constant inventory of 43 kg. The superficial gas velocity varied from 0.2～0.54 m/s in the draft tube (based on the cross-sectional area of the draft tube) and was maintained at 0.08 m/s in the annulus (based on the cross-sectional area of the annulus).

A PV-4A Particle Density and Velocity Analyzer (Institute of Process Engineering, Chinese Academy of Sciences) was used here to measure the local bed density inside the bed. In order to reduce the influence on local flow field, a small probe with a *Φ*3.8 mm tip was employed. An experiment was conducted to determine this relationship, by relating the cross-sectional time-averaged output signal *V* to bed density calculated from the pressure drop measured by a differential pressure transducer. The calibration experiment was conducted in a gas-solid fluidized bed of 150 mm ID and 1m height. The pressure tranducers were mounted 400 mm above the gas distributor, with an interval of 100 mm, and the optical probe was located at the midpoint of the interval. Then, *V* is calculated by integrating the time-averaged output signals at different radial positions V_r over the entire cross section.

$$V = \frac{\sum V_r A_r}{\sum A_r} \tag{1}$$

The relationship between the output signals and the bed density was fitted with an error of less than 5% by

$$\bar{\rho} = 58.8e^{0.645V} \tag{2}$$

Statistical analysis was made to obtain probability density function (PDF) of transient signals. As shown in Fig.2, results reveal a typical bimodal distribution of PDF. The two peaks can be respectively simulated by a log-normal distribution and a Gaussion distribution. The bimodal profile can be described by the following correlation.

$$f(\varepsilon_s)=\frac{1}{\sigma_{sd}\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\varepsilon_{sd}-\mu_{sd}}{\sigma_{sd}}\right)^2\right](1-f_1)+\frac{1}{\sigma_{sl}\varepsilon_{sl}\sqrt{2\pi}}\exp\left[-\frac{1}{2\sigma_{sl}^2}(\ln\varepsilon_{sl}-\mu_{sl})^2\right]f_1 \tag{3}$$

where f_l is volume fraction of the bubble phase.

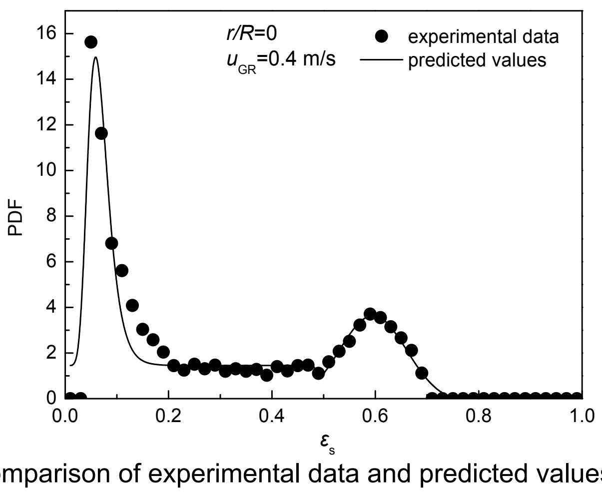
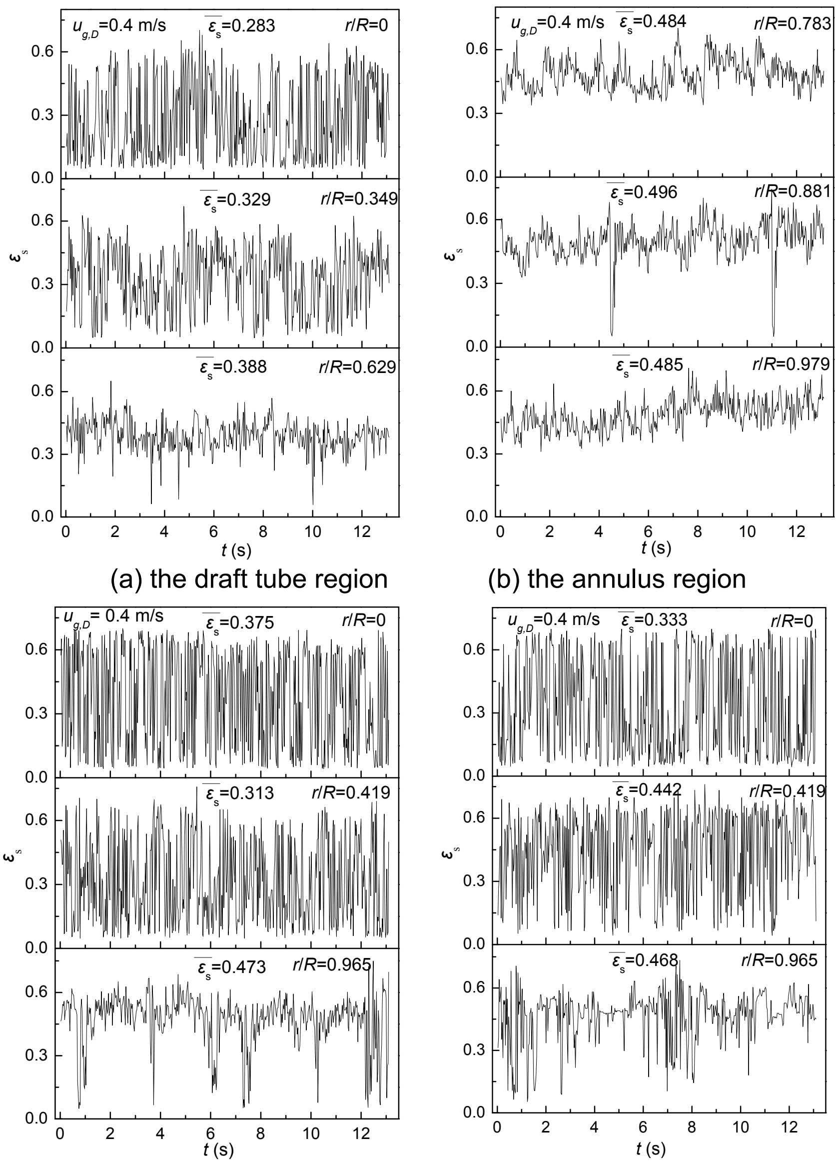


Fig.2 Comparison of experimental data and predicted values of PDF

RESULTS AND DISCUSS

Characteristics of transient solid holdup signals

Local solid holdup signals registered in GSALR were given in Fig.3, showing significant variation with radial positions and regions.



(a) the draft tube region (b) the annulus region

(c) the bottom region (d) the top region

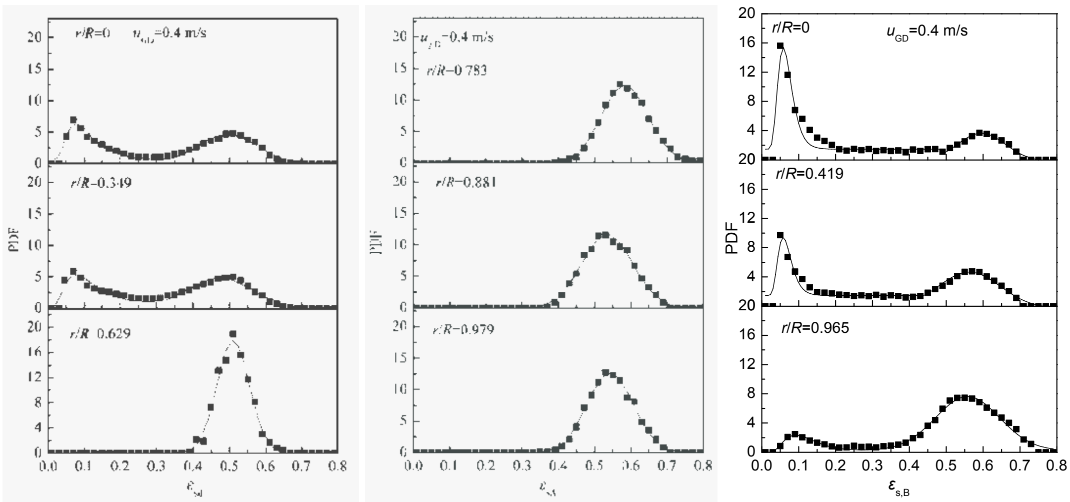
Fig.3 Transient signals registered in different regions in GSALR

In the draft tube region, signals amplitude decreases from center toward the wall of the draft tube, indicating a fact that fewer bubbles appear near the wall compared with the center. As a result, the mean solid holdup increases with radial positions. Similar phenomena are also observed in the bottom and top regions, but the signals amplitude seems greater than that in the draft tube region, suggesting stronger interaction between gas and particles. In the bottom region, dramatic drops of solid holdup appear at the radial position out of the aerated area of the draft tube gas distributor (*r/R*=0.769), as signifies of the bubbles carried by circulating particles. In the annulus region variation of solid holdup along radial direction seems small, because the annulus region is narrow.

Probability density function of local solid holdup signals

Because of the interaction between gas and particles, transient signals registered at a certain position in a fluidized bed may contain multi components originating from different sources, such as pure gas, particles dispersed in bubbles, the emulsion, bubble wakes and clouds. The complex hydrodynamics of the two phases cannot be represented by time- or volume-averaged parameters alone. Various methods have been employed to interpret transient signals, such as statistic method, chaos analysis, wavelet analysisand auto-correlation analysis. In the present work, the statistic method was employed to gain further insight into the nature of the two-phase flow structure.

Probability density function (PDF) of local solid holdup signals registered at different radial positions and in different regions in GSALR is shown in Fig. 4. The PDF evolution seems different in morphology, but shows a typical bimodal distribution in most cases, suggesting significantly varying flow structure with spatial positions. The peak characterized by a long tail and relatively low solid holdup corresponds to the bubble phase, which indicates a fact that bubbles in gas-solid fluidized bed contain particles. Solid concentration inside bubbles is affected by multi factors, such as bubble number and size, bubble breakup and coalescence, relative velocity between bubbles and the emulsion, and even particle physical properties (4,5). The other peak of high solid concentration represents the emulsion phase. As shown in Fig.4, the widely distributed solid concentration indicates that particles in the emulsion are not uniformly suspended as described by the two-phase theory (3); instead, they exist as dispersed particles and agglomerates as reported by Mostoufi and Chaouki (8). Such a phenomenon is also related to bubble motion, particle properties and flow regimes (4,5).



(a) the draft tube region (b) the annulus region (c) the bottom region

Fig.4 probability of local solid holdup signals

Fig.4 (a) reveals that the two peaks are comparable in the center of the draft tube. With moving towards the wall, the peak of the bubble phase gradually becomes smaller and finally disappears in the vicinity of the wall of the draft tube, while the peak representing the emulsion phase becomes greater and wider. This demonstrates a fact that more bubbles prefer to move in the center of the bed, leading to stronger interaction of the two phases in the center than near the wall. Compared with that in the draft tube region, the peak corresponding to the bubble phase seems narrower and greater in the bottom region. In the present work, the bottom region is considerably affected by the draft tube gas distributor, so the bubble size in the region is closer than that in the draft tube region, leading to close solid concentration inside bubbles. Furthermore, as shown in Fig.4 (c) bubbles still can be found near the wall of the reactor, mostly originating from those carried by circulating particles and from gas bypassing. Fig.4 (b) illustrates PDF profiles in the annulus region. The evolution along the radial direction seems approximately same because of narrow space in the annulus region. It is seen that the peak corresponding to the bubble phase disappears in Fig.4 (b), indicating that few bubbles exist in the annulus region.

Standard deviation of PDF of the two phases

The strong and complex interaction between the bubble and emulsion phases results in penetration and distribution between the two phases, leading to particles inside bubbles and non-uniformly fluidized emulsion. Particles inside bubbles may exist in two ways, namely dispersed particles and the agglomerates (8). Up to now, the mechanism associated with particles entering bubbles is not well understood, but it can be considered to be related to the two phase interaction, such as bubble coalescence and breakup. Clearly, the contact of gas and particles occurring in bubbles is considerably influenced by the solid volume fraction. Because particles may not be uniformly dispersed inside bubbles (8), the two-phase contact is also related to concentration variation of the solid phase, which can be characterized by standard deviation of PDF of the bubble phase. Fig.5 illustrates the mean solid holdup and standard deviation of PDF of the bubble phase in the draft tube region. It is seen that the mean solid holdup of the bubble phase increases with increasing superficial gas velocity, ranging from 0.011 (16.5 kg/m^3) to 0.115 (172 kg/m^3). It is because that increasing gas velocity results in intensive bubble coalescence and breakup, and consequently increases particle concentration and enhances gas-solid contact inside bubbles. The mean solid holdup slightly decreases with radial direction, probably caused by radially weakened bubbles motion. Fig. 5 also reveals that the standard deviation of PDF of the bubble phase increases as superficial gas velocity increases, suggesting enhanced non-uniformly distributed particles with gas velocity. Furthermore, it is seen that the mean solid holdup and standard deviation for $u_{G,D}$ of 0.4 and 0.54 m/s is considerably greater than that for $u_{G,D}$ of 0.2 m/s. Previous work shows that the fluidized bed in the draft tube transfers to turbulent bed when $u_{G,D}$ is higher than 0.3 m/s, leading to significantly intensive two-phase interaction and enhanced two-phase contact.

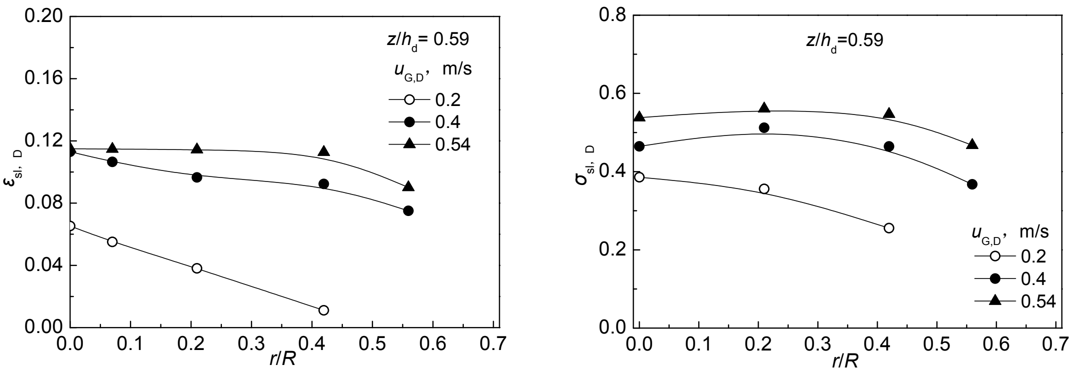


Fig. 5 Mean solid holdup and standard deviation of PDF of the bubble phase in the draft tube region

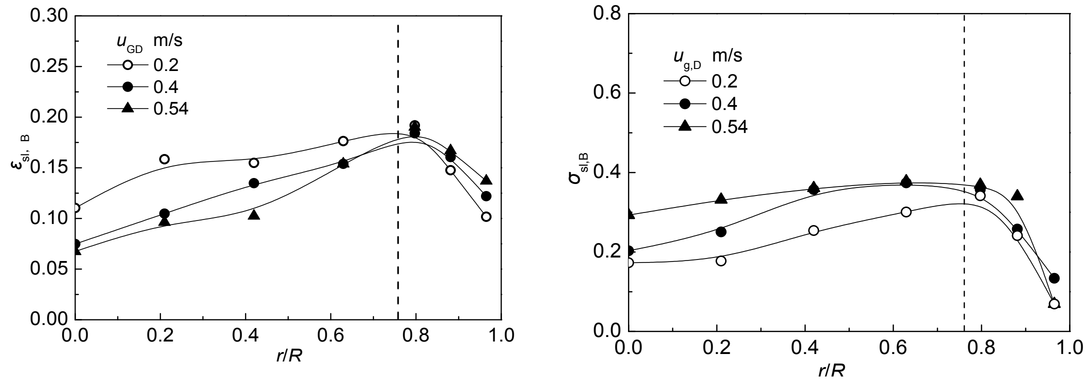


Fig. 6 Mean solid holdup and standard deviation of PDF of the bubble phase in the bottom region

Fig. 6 illustrates the mean solid holdup and standard deviation of PDF of the bubble phase in the bottom region. Compared with the draft tube, the bottom region has a reverse evolution by decreasing mean solid holdup with increasing superficial gas velocity for $r/R \leqslant 0.769$. The height level of measurement point is only 32 mm above the draft tube gas distributor, suggesting that measurements are governed by jets of distributor rather than two-phase interaction. The greater the gas velocity is, the lower the mean solid concentration of bubbles is. In Fig.6 (a), the dashed line represents the object of the draft tube. It is seen that the mean solid holdup firstly increases along radial direction, reaches maximum near the dashed line and then decreases in the vicinity of the wall. In the bottom region, a cross flow of the two phases occurrs at r/R=0.6~0.85, with particles moving horizontally while bubbles rising vertically, leading to significant interaction between phases and excellent gas-particle contact inside bubbles. The standard deviation of PDF of the bubble phase is shown in Fig.6 (b). It also reaches the maximum at r/R=0.6~0.85, mainly arising from strong interaction between phases.

CONCLUSION

Experiments have been conducted in a cold mode apparatus. Transient solid holdup signals were registered by a reflective-type optical fiber probe. Statistical analysis has been made and the following conclusion is obtained.

(1) PDF curve of transient signals can be mathematically described by coupling a log-normal distribution and a Gaussion distribution.
(2) Mean solid holdup of the bubble phase varies with spatial positions and superficial gas velocity, mainly ranging from 0.1 to 0.15.
(3) In the draft tube region, increasing superficial gas velocity results in increasing

mean solid holdup and greater standard deviation of the bubble phase, and thereby enhanced gas-particle contact.

(4) In the bottom region, mean solid holdup decreases as superficial gas velocity increases, mainly governed by gas distributor jets.

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NOTATION

ε_s	solid holdup
$\varepsilon_{sd}, \varepsilon_{sl}$	mean Solid holdup of the emulsion and bubble phases
$\overline{\varepsilon}_{sb}$	mean solid holdup of the bubble phase
σ_{sd}, σ_{sl}	standard deviation for the emulsion and bubble phases
μ_{sd}, μ_{sl}	parameters
Subscript	
A	annulus region
B	bottom region
D	draft tube region
T	top region or gas –solid separator region

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KEY WORDS

gas-solid fluidized bed, fluidization, flow structure, two phases, solid holdup, bubbling fluidized bed, turbulent fluidized bed, solid holdup fluctuation, transient signals, clusters