Stochastic Analysis of Gas-Liquid-Solid Flow in Three-Phase Circulating Fluidized Beds

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Characteristics of gas-liquid-solid flow behavior in a riser are investigated in a three-phase circulating fluidized bed (0.102 m I.D. × 3.5 m in height). Local gas holdup, solid holdup distribution, and pressure fluctuations in the riser have been measured and utilized to describe the gas-liquid-solid flow behavior more conveniently. The resultant pressure fluctuations have been analyzed by adopting the chaos method: The time series of pressure fluctuations have been interpreted by means of phase space portraits and Kolmogorov entropy. The effects of gas and liquid velocities and solid circulation rate on the local gas holdup, solid axial distribution, phase space portrait, and Kolmogorov entropy of pressure fluctuations, as well as on the flow behavior of gas-liquid-solid mixture in the riser are determined. It is found that pressure fluctuations can be a quantitative tool to characterize the flow behavior and flow regime transition of multiphases in the riser. The relations between the pressure fluctuations and the distribution of phase holdup and flow regime in the riser are also discussed.

Introduction

A three-phase circulating fluidized bed can be utilized effectively as a multiphase (gas-liquid-solid) flow reactor, bioreactor or adsorption and contacting system, especially when the viscosity of the continuous liquid medium is relatively high. It has been generally understood that a conventional three-phase fluidized bed are significantly restricted in it’s use as a reactor or a contactor when the small or light particles are fluidized in the viscous liquid medium, which is often encountered for practical application of three-phase fluidized beds. In addition to several unique advantages of three-phase fluidized beds, the three-phase circulating fluidized beds can minimize the dead zone and increase the contacting efficiency among gas, liquid and solid phases, in the riser by enhancing the shear stress at the interfaces owing to the extremely high liquid velocity.

These advantages result in considerable increases in the fractional conversion as well as production efficiency per unit cross-sectional area of the system. Moreover, the deactivated catalyst can be regenerated continuously by means of a circulating fluidization mode (Liang et al., 1995a, 1995b, 1997; Kim et al., 1999). However, there has been little attention on the three-phase circulating fluidized bed until now, even on the fundamental hydrodynamics (Kim and Kang, 1996, 1997).

In the present study, thus, the hydrodynamic characteristics of three-phase circulating fluidized beds have been investigated by adopting a somewhat novel chaos method. More specifically, the time series of pressure fluctuations, which can visualize the gas-liquid-solid flow behavior in the riser directly, have been measured and analyzed by means of chaos analysis to express the flow characteristics by means of stochastic tools such as phase space portraits and Kolmogorov entropy. Local gas holdup and solid holdup distribution in the axial direction have also been discussed to examine the flow regime transition in the riser. The results of this study can be utilized for the design, scale-up, and determination of optimum operating conditions of three-phase circulating fluidized bed reactors or contactors.

1. Analysis

1.1 Phase space portraits

The multidimensional phase space portraits can be constructed from the pressure fluctuation time series by means of the time delay method (Packard et
be used more easily to scale the time dependent behavior of gas-liquid-solid flow in the riser. The amount of the information needed to specify the evolution in time of the system during the interval \([t_i, t_j]\) is given by (Van der Stappen et al., 1992)

\[ I(t_i + t_j) = I(t_i) + K_2 \times (t_j - t_i) \]

\[ \text{for } (t_j - t_i) \to \infty \]  

(2)

In this equation, the invariant parameter \(K_2\) is the Kolmogorov entropy. The Kolmogorov entropy can actually be obtained by considering the fraction of pairs separated by a distance smaller than a certain maximum length, given the embedding dimension \(p\) as

\[ K_2(r_0, p) \propto \exp(-K_2 p \tau) \]

\[ \text{for } p \to \infty, r_0 \to \infty \] 

(3)

where \(\tau\) is time delay in the reconstruction.

2. Experiment

Experiments were carried out in the riser of a three-phase circulating fluidized bed which is composed of three main sections; the riser column, gas-liquid-solid separator, and solid recycle device, as can be seen in Fig. 1. The riser and solid recycle device were made of several pieces of acrylic column. The diameter and height of the riser were 0.102 m ID and 3.5 m, respectively. The distributor was situated between the main column section and a 0.2 m high stainless steel distributor box into which water was introduced through a 0.025 m pipe from the liquid reservoir. Oil-free compressed air was fed to the column through a pressure regulator, filter and a calibrated rotameter. It was admitted to the column through four 3.0 mm ID perforated pipes drilled horizontally in the grid. The pipes were evenly spaced across the grid having 12 holes whose diameters were 1 mm.

The solid particles were returned to the bottom of the riser through the solid recycle device. The solid circulation rate was determined by measuring the amounts of solid piled up above the butterfly valve in the solid recycle device (Kang et al., 1997b, 2000b; Kim et al., 1999).

Glass beads whose diameter and density were 2.1 mm and 2,500 kg/m³, respectively, were used as the fluidized solid particle, and compressed air and tap water were used as the gas and liquid phases, respectively.

2.1 Local phase holdup measurement

The local gas holdup was measured by means of a dual electrical resistivity probe system (Matsuura and Fan, 1984; Idogawa et al., 1986; Kang et al., 2000a).

The probe applied with a 1.75 DC voltage detected the difference in conductivity of the gas and liquid. The dual electrical resistivity probe, which was installed
at either 0.5, 0.9, 1.3, or 1.7 m from the distributor, consisted of two 7 mm diameter stainless steel pipes coated with epoxy resin. It has been understood that the solid particle cannot interfere with the measurement of gas holdup, because the conductivity difference between the gas and liquid (or solid) is very high (Liang et al., 1995a, 1995b). Also, the diameter of the probe is too small to be compared with that of the riser column, thus, the probe cannot interfere with the flow in the riser column considerably. The bubble properties, including the gas holdup, have been measured by this method without significant error in three-phase fluidized beds whose solid holdup is higher than that in three-phase circulating fluidized beds (Kim and Kang, 1996, 1997). The vertical distance between the two tips of the probe was 2 mm. The probe was located at the center as well as at 0.3, 0.6 and 0.9 as measured in dimensionless radial coordinate (r/R) between the wall and the center of the column. The tips of the probe, which are made of platinum wire, had a diameter of 0.2 mm.

The analog signals obtained from each probe circuit were processed to produce digital data. The preselected sampling rate at the personal computer with the DT3001 Lab Card was 500 µs. The total sampling time was 15 s. The signals were processed off-line. The local gas holdup has been calculated from the relationship between the digitized probe signals and the bubble dwell and lag time (Yu and Kim, 1991; Kang et al., 2000a). The cross-sectional averaged value of gas holdup is regarded as the gas holdup at the selected height of the bed. Individual phase holdups have been determined by means of Eqs. (4) and (5) with the knowledge of measured values of ΔP/ΔZ and gas holdup (Liang et al., 1995a; Kim et al., 1999).

\[
\Delta P/\Delta Z = (\rho_G \varepsilon_G + \rho_L \varepsilon_L + \rho_S \varepsilon_S)g \tag{4}
\]

\[
\varepsilon_G + \varepsilon_L + \varepsilon_S = 1.0 \tag{5}
\]

### 2.2 Pressure drop and pressure fluctuations measurement

The static and dynamic pressures were measured by means of pressure sensors. A pressure tap for measuring the pressure fluctuations was mounted flush with the wall of the column in the test section, which is located 1.0 m above the distributor. To measure the static pressure drop in the riser, 15 pressure taps were installed in the wall of the column with intervals 0.2 m from the distributor. The pressure sensors were of semiconductor type (Coppel Electronics) that have enough fast response time to measure the dynamic pressure fluctuations in the test section. The output voltage from the pressure transducer, which is proportional to the pressure fluctuations or static pressure, was processed by means of a data acquisition system (Data Precision Model, DT3001) and a personal computer. The voltage-time signals, corresponding to the pressure-time signals, were sampled at a rate of 0.005 sec and stored in the data acquisition system. The total acquisition time was 15 sec having 3000 data points. This combination of sampling rate and time can detect the full spectrum of hydrodynamic signals (200 Hz) in multiphase flow systems (Kang et al., 1996, 1997a).
of particle. This may be due to that they did not control and maintain the solid circulation rate at a constant value.

### 3.2 Local phase holdup in the riser

Typical example of output signals measured by the resistivity probe can be seen in Fig. 3. These data have been reformed and digitized to produce the digital data from which the local gas holdup has been calculated.

**Figure 4** shows the radial distribution of gas holdup in the test section of the riser. It can be noted in this figure that the local gas holdup tends to increase near the center of the riser. However, the difference of local gas holdup with the variation of radial direction decreases with increasing liquid velocity. This may be due to the increase of turbulence which is effective to break and distribute the rising bubbles, owing to the higher liquid velocity.

**Figure 5** shows the solid holdup variation with bed height in the riser. Note in this figure that the solid holdup, \( \varepsilon_s \), decreases gradually with increasing bed height when \( U_L \) is 0.21 m/s, however, when \( U_L \) is 0.30 m/s, the \( \varepsilon_s \) value does not change significantly with increasing bed height at a constant solid circulation rate. In other words, the axial solid distribution in the test section is almost uniform at sufficiently high liquid velocity over the particle terminal velocity. Actually, it can be easily observed that the flow of gas-liquid-solid mixture becomes uniform and less complex at the higher liquid velocity condition over 0.30 m/s.

### 3.3 Pressure fluctuations in the riser

The flow characteristics, holdup distribution, and flow regime transition in the multi-phase flow systems have been successfully investigated by analyzing the dynamic pressure fluctuations (Drahos et al., 1992; Fan et al., 1993; Kikuchi et al., 1997; Kang et al., 1997a, 1997b).

Typical time series of pressure fluctuations can be seen in Figs. 6 and 7. Note in these figures that the pressure fluctuations are strongly dependant upon the flow behavior of the multiphase in the riser; the signal, when \( U_L \) is 0.25 m/s, is more complex than that when \( U_L \) is 0.23 m/s (Fig. 6), however the amplitude of pressure fluctuation signals decreases with increasing \( U_L \) in the range greater than 0.25 m/s. From Fig. 7,
it is anticipated that the increase of solid circulation rate, $G_s$, can lead to a more complex system. These pressure fluctuations can be utilized more conveniently to visualize the complex flow behavior by means of phase space portraits in the reconstructed trajectory. Examples of the phase space portraits from the pressure fluctuation data can be seen in Figs. 8–10. The optimum value of time lag, $\tau$, for construction of the attractor is chosen when the mutual information function of the discrete data sets attains its first minimum (Karamavruc et al., 1995). It can be noted in these figures that the attractor becomes more scattered and complex with increasing $U_G$ and $G_s$, however, it tends to be less complicated with increasing $U_L$ greater than 0.25 m/s, when the solid entrainment tends to significant and the local pressure drop at three parts of the riser becomes almost same. The increase of $U_G$ results in the increase of bubble size which eventually results in a less uniform flow of bubbles, thus, the loop of the portrait tends to be scattered with increasing $U_G$. In the $U_L$ range of solid circulation ($U_L$ is greater than 0.25 m/s), the increase of $U_L$ leads to the increase of turbulence to break down large bubbles rising in the test section, which consequently results in the decrease of bubble size. This leads to the more uniform distribution of bubbles in the flow of multiphases. Thus, the loop of the attractor tends to be less scattered with increasing $U_L$ (Fig. 9).

The flow behavior of a gas-liquid-solid mixture in the riser seems to be more complicated with the increase in solid circulation rate (Fig. 10). This is because, the increase in solid holdup owing to the increase of $G_s$ can promote the contacting and splitting probability among gas, liquid and solid phases, which in turn disturb the uniform flow of gas-liquid mixture flowing upward by means of, namely, hindrance effects.

To elucidate the complicated and stochastic flow behavior of a gas-liquid-solid mixture in the test section more easily and quantitatively, the Kolmogorov entropy of pressure fluctuations has been calculated, since the Kolmogorov entropy can be a parameter to predict the rate of generation or disappearance of intrinsic information in the system. As expected from the attractor in the phase space (Fig. 8), the value of Kolmogorov entropy increases with increasing $U_G$ (Fig. 11). This may be due to the fact that the bubble holdup and its coalescence increase with increasing $U_G$, thus
the size of the bubble increases. These directly make the system more complex, because the individual random motion of bubbles becomes significant with increasing bubble size (Kim and Kang, 1996, 1997).

The effects of $U_L$ on the Kolmogorov entropy value, $K_2$, can be seen in Fig. 12. As can be anticipated in Fig. 9, the $K_2$ value exhibits a local maximum with increasing $U_L$. Note that a three-phase circulating mode can be established for the $U_L$ range greater than 0.25 m/s. It can also be noted in this figure that the gas-liquid-solid flow behavior in the riser becomes more regular with increasing $U_L$ in the circulating fluidized beds. The quantitative increase trends of irregularity or randomness of gas-liquid-solid flow behavior in the riser can be seen in Fig. 13, with an increase in the solid circulation rate, $G_S$.

**Conclusion**

The highly complex and irregular behavior of gas-liquid-solid flow in the riser of a circulating fluidized bed has been effectively and quantitatively analyzed by adopting the chaos analysis theory; the multiphase flow behavior has been visualized conveniently by means of phase space portraits of resultant pressure fluctuations and expressed quantitatively by Kolmogorov entropy. It has been found that the local
pressure drop with the variation of axial direction of the riser becomes almost the same at a critical liquid velocity, over which the solid circulation rate has to be controlled and maintained at a constant value in order to maintain uniform solid holdup in the axial direction. The local gas holdup is higher near the center than that at the wall side of the riser, but the difference of the local gas holdup is decreased considerably with increasing liquid velocity. The flow behavior tends to be more complex and irregular with increasing gas velocity and solid circulating rate, however, the irregularity or randomness decreases with increasing liquid velocity under constant gas velocity and solid circulation rate conditions.

Acknowledgment
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Nomenclature

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>$G_S$</td>
<td>solid circulation rate</td>
<td>kg/(m²·s)</td>
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<td>$K_2$</td>
<td>Kolmogorov entropy</td>
<td>bits/s</td>
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<tr>
<td>$k$</td>
<td>constant</td>
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<tr>
<td>$m$</td>
<td>number of data point</td>
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<td>$P$</td>
<td>pressure</td>
<td>volt</td>
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<td>$\Delta P/\Delta Z$</td>
<td>static pressure drop in the riser</td>
<td>kPa/m</td>
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<td>$\rho$</td>
<td>embedded dimension</td>
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<tr>
<td>$t$</td>
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<td>$U_G$</td>
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<td>$U_L$</td>
<td>liquid velocity</td>
<td>m/s</td>
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<tr>
<td>$X(t)$</td>
<td>time series of pressure fluctuations</td>
<td>volt</td>
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<tr>
<td>$Z_{1}$</td>
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<td>s</td>
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<td>$\rho$</td>
<td>density</td>
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<tr>
<td>$\varepsilon$</td>
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<td>$G$</td>
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Literature Cited


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