# Mechanism of Flow Regime Transition from Bubbling to Turbulent Fluidization

**P. Cai**
**Y. Jin**
**Z.-Q. Yu**
**Z.-W. Wang**
Department of Chemical Engineering
Tsinghua University
Beijing 100084, China

The flow regimes of a dense-phase gas-solid fluidized bed have become a topic of increasing interest as a result of intensive development in fluidization research. Through a plot of the bed's pressure fluctuation vs. gas velocity curve, most investigators have determined the critical transition velocity from bubbling to turbulent fluidization (Yerushalmi and Cankurt, 1979; Staub, 1982; Jin et al., 1986). This critical velocity, $u_c$, was defined as the velocity corresponding to the peak point of that curve. However, the mechanism of this flow regime transition has not been realized clearly. The mechanism that can fairly fit the experimental phenomena is still not available, although some attempts have been proposed (Yang, 1984). The present work is focused on revealing that mechanism.

## Experimental Arrangement

Experiments were conducted in two fluidized beds, a 0.139m dia. bed and a 0.012 × 0.3 m two-dimensional bed, at ambient temperature and pressure. Two kinds of spherical particles were employed (silica gel A: $d_p = 476 \times 10^{-6}$ m, $\rho_p = 834$ kg/m$^3$; silica gel B: $d_p = 280 \times 10^{-6}$ m, $\rho_p = 706$ kg/m$^3$). Two pressure transducers, $A$ and $B$, were installed on the wall of the bed with a vertical separation $\Delta L = 0.1$ m, so as to sample the pressure fluctuation signals from the dense phase.

## Analytical Theory

The signals from the two transducers, $P_x(t)$ and $P_y(t)$, were processed as follows:

$$S_i = \frac{1}{T}\int_0^T \left| P(t) - \frac{1}{T}\int_0^T P(t)\,dt \right| dt \quad (i = x, y) \tag{1}$$

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)\,G_{yy}(f)} \tag{2}$$

where $G_{xx}(f)$, $G_{yy}(f)$ are the autopower spectra of signals $P_x(t)$ and $P_y(t)$, respectively. $G_{xy}(f)$ is the cross-power spectrum of signals $P_x(t)$ and $P_y(t)$. $G_{xx}(f)$, $G_{yy}(f)$, and $G_{xy}(f)$ are defined as

$$G_{xx}(f) = \frac{2}{T}|P_x(f)|^2 = \frac{2}{T}P_x^*(f)\,P_x(f) \tag{3}$$

$$G_{yy}(f) = \frac{2}{T}|P_y(f)|^2 = \frac{2}{T}P_y^*(f)\,P_y(f) \tag{4}$$

$$G_{xy}(f) = \frac{2}{T}P_x(f)\,P_y(f) \tag{5}$$

where $P_x^*(f)$ and $P_y^*(f)$ are the conjugate complex of $P_x(f)$ and $P_y(f)$. $P_x(f)$ and $P_y(f)$ are obtained from the Fourier transformation of signals $P_x(t)$ and $P_y(t)$ over the sampling time interval, $T$. So, they are the signals in the frequency domain:

$$P_x(f) = \int_0^T P_x(t)\,e^{-j2\pi ft}\,dt \tag{6}$$

$$P_y(f) = \int_0^T P_y(t)\,e^{-j2\pi ft}\,dt \tag{7}$$

The flow regimes can be mapped out on a plot of $S$ vs. $u$ as shown in Figure 1. The critical velocity $u_c$ is indicated in that figure.

The coherence function $\gamma_{xy}^2(f)$ can be used to measure the similarity of two signals at the frequency $f$ (Bendat and Piersol, 1971). Since the bed pressure fluctuation is a kind of random signal made up of the components at different frequencies ($f_1 \le f \le f_2$), a new concept, the average coherence function, $(\overline{\gamma_{xy}^2})$, was proposed to measure the similarity between the signals (hence the bubbles) at the two measuring levels of the

Correspondence concerning this paper should be addressed to P. Cai.

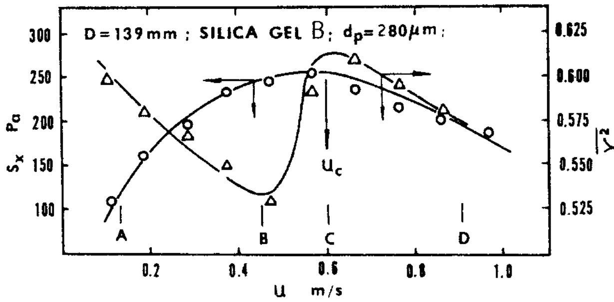


**Figure 1. Variation of $\overline{\gamma_{xy}^2}$ and $S$ vs. gas velocity.**

bed:

$$\overline{\gamma_{xy}^2} = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} \gamma_{xy}^2(f)\, df \tag{8}$$

For a regular gas-solid fluidized bed, the selection of $f_1 = 0$ Hz and $f_2 = 10$ Hz would be suitable (Cai, 1989). The following expression is always satisfied in linear systems (Bendat and Piersol, 1971):

$$0 \leq \gamma_{xy}^2(f) \leq 1 \tag{9}$$

Thus,

$$0 \leq \overline{\gamma_{xy}^2} \leq 1 \tag{10}$$

If $\gamma_{xy}^2(f) = 1$, it can be considered that the two signals are completely analogous at frequency $f$. If $\gamma_{xy}^2(f) = 0$, the two signals are totally different at frequency $f$. The fluidized suspension between the measuring levels has been proved to be a linear system as long as $\Delta L \leq 0.3$ m (Cai, 1989). In this way, the variation of bubbles in this system could be determined quantitatively by $\overline{\gamma_{xy}^2}$. The smaller the $\overline{\gamma_{xy}^2}$, the more significant the bubble variation. $\overline{\gamma_{xy}^2} = 1$ corresponds to no change of the bubbles, and $\overline{\gamma_{xy}^2} = 0$ corresponds to total change of the bubbles.

## Results and Discussion

The relationship between $\overline{\gamma_{xy}^2}$ and gas velocity is also plotted in Figure 1. As shown, the operating region can be divided into three subregions along the increase of gas velocity axis. The behavior of bubbles in each subregion is different.

### *Subregion between points A and B*

As the gas velocity increases, the value of $\overline{\gamma_{xy}^2}$ decreases, that is, the variation of the bubbles is enhanced. At the same time, the average magnitude of pressure fluctuation, $S$, rises with increasing gas velocity. That means the predominant variation of bubbles in this subregion is coalescence. The prevailing flow regime is bubbling fluidization.

### *Subregion between points C and D*

Along with the increase of gas velocity, the variation of bubbles is enhanced because of the decrease of $\overline{\gamma_{xy}^2}$. $S$ decreases with increasing gas velocity also. That means the predominant variation of bubbles in this subregion is breaking-up. The prevailing flow regime is turbulent fluidization.

### *Subregion between points B and C*

In this small subregion, the extent of bubble coalescence makes the bubble size be the same order of magnitude as the distance between the two measuring points, $\Delta L$. Further variation of the bubbles will not cause a significant change of the pressure fluctuation signal. So, the signals' similarity tends to be improved ($\overline{\gamma_{xy}^2}$ increases). The gradual increase of $S$ and the increase of $\overline{\gamma_{xy}^2}$ along with increasing gas velocity indicates that the predominant variation of the bubbles is still coalescence. The prevailing flow regime could be considered as the upper edge of bubbling fluidization. From the viewpoint of signal characteristics, this subregion could also be called the transition region. The extent of this region depends on the bed size and the distance between the measuring levels, $\Delta L$. Further experiments show that $\Delta L$ does not affect the position of point $C$ as long as the bed size is constant.

Considering the identical correspondence of point $C$ with the flow regime transition velocity $u_c$, the mechanism of flow regime transition can be described as follows: When the predominant variation of the bubbles changes from coalescence to breaking-up, the prevailing flow regime transfers from bubbling fluidization to turbulent fluidization.

## Notation

$d_p$ = average diameter of particles, m
$f$ = frequency, Hz
$G_{ii}(f)$ = autopower spectrum of signal $P_i(t)$, ($i = x, y$)
$G_{xy}(f)$ = cross-power spectrum of signals $P_x(t)$ and $P_y(t)$
$P(f)$ = bed pressure fluctuation signal (frequency domain)
$P(t)$ = bed pressure fluctuation signal (time domain)
$S$ = average magnitude of pressure fluctuation, Pa
$t$ = time, s
$T$ = sampling period, s
$u$ = superficial gas velocity, m/s

### *Greek letters*

$\gamma_{xy}^2(f)$ = coherence function
$\overline{\gamma_{xy}^2}$ = average coherence function in the interval $f_1 \leq f \leq f_2$
$\Delta L$ = vertical distance between the two measuring points (levels), m

### *Subscripts*

$c$ = critical (transition from bubbling to turbulent fluidization)
$x$ = measuring point (level) $x$
$y$ = measuring point (level) $y$

## Literature Cited


Bendat, J. S., and A. G. Piersol, *Random Data, Analysis and Measurement Procedures*, Wiley-Interscience, New York (1971).

Cai, P., "Flow Regime Transition in Dense Phase Gas-Solid Fluidized Bed," Ph.D. Diss., Tsinghua Univ. (cooperative program with Ohio State Univ.), Beijing (1989).

Jin, Y., Z.-Q. Yu, Z.-W. Wang, and P. Cai, "A Criterion for Transition from Bubbling to Turbulent Fluidization," *Fluidization V*, K. Ostergaard and A. Sorensen, eds., Eng. Found., New York, 289 (1986).

Staub, F. W., "Flow and Heat Transfer in Large-Particle Turbulent Fluidized Bed," *Proc. Joint Meet. Chem. Eng., CIESC, and AIChE Beijing)*, **1**, 411 (1982).

Yang, W.-C., "Mechanical Models for Transitions between Regimes of Fluidization," *AIChE J.*, **30**, 1025 (1984).

Yerushalmi, J., and N. T. Cankurt, "Further Studies of the Regimes of Fluidization," *Powder Technol.*, **24**, 187 (1979).


*Manuscript received Oct. 16, 1989, and revision received Apr. 9, 1990.*