HYDRODYNAMIC BEHAVIOR OF A BINARY SOLIDS FLUIDIZED BED

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This paper presents a study on the hydrodynamic behavior of a fluidized bed containing mixtures of solids of different sizes and densities. The transition velocity from bubbling to turbulent fluidization and solids holdup of the dense bed in different fluidization regimes were experimentally determined. The onset velocity to turbulent fluidization was found to increase with increasing fraction of coarse solids. Solids holdups changed differently with gas velocity and fraction of coarse particles in bubbling and turbulent fluidization regimes. As a quantitative measure for describing the complexity or the self-affine property of the time series signals, a fractal analysis was introduced and related to the hydrodynamics of the fluidized beds. A correlation to predict the transition velocity of a binary solids fluidized bed was also developed in this paper.

Introduction

Most gas fluidized beds, which are operated under bubbling or turbulent fluidization regimes (e. g., Grace, 1986), contain non-uniform mixtures of particles. For some applications, the solid materials (reactants or catalysts) are composed of different sizes and/or densities (e. g., Rowe and Nienow, 1975). For some other cases, the binary or multi-solids systems are formed by addition of other kinds of solids that differ from the original bed material (Aznar *et al.*, 1992). This has been proved useful and efficient when some solid materials such as biomass-agriculture and forest residues and certain urban and industrial wastes are processed, because these solids cannot be fluidized properly by their nature (Aznar *et al.*, 1992). To increase the fines holdup, and thus to improve the contacting between gas and fine solids in transport risers, addition of coarse particles may also be necessary (Bi *et al.*, 1992). Therefore, a good hydrodynamic understanding concerning this kind of multi-solids fluidized bed is essential for proper design and operation.

Research of the hydrodynamic behavior of fluidized beds containing non-uniform mixtures of particles has, so far, largely been confined to binary mixtures. Most of these research works have paid attention to solids mixing and segregation that are expected in relatively lower gas velocities (Rowe and Nienow, 1975, Nienow *et al.*, 1987, Hoffmann *et al.*, 1993). Many authors also studied the minimum and completed fluidization velocities of such systems (Rowe and Nienow, 1975, Aznar *et al.*, 1992). Note that most successful applications of binary solids fluidized beds,

however, involve higher gas velocities in which well-defined bubbling or slugging has given way to a more turbulent hydrodynamic region. Research at higher gas velocities, however, is scarce.

In this paper, we report results of the hydrodynamic characteristics including transition velocity U_c , the solids holdup of the dense bed in a binary solids fluidized bed. Experiments were conducted by changing the fraction of coarser silica sand particles in the FCC/silica sand mixtures in the range of 0 to 100 wt%. The recorded time series have also been characterized in terms of Hurst's rescaled range (R/S) analysis. This has yielded estimates for the so-called Hurst exponent and eventually the fractal dimension of the time series of pressure fluctuations. The fractal dimension was then related to the hydrodynamic behavior of the fluidized bed.

1. Determination of Fractal Dimension: the Rescaled Range (R/S) Analysis

Fluidized beds can be considered as chaotic systems due to the influence of a variety of phenomena, including bubble formation, coalescence and breakup, as well as the motion of fluidized particles. Pressure fluctuations are direct results of these phenomena. In general, any of the pressure fluctuation signals from fluidized beds consists of two major components, a periodic component and a random component (Fan *et al.*, 1990). As observed by many investigators (e. g., Chehbouni *et al.*, 1994), the latter becomes more significant when gas velocity is increased. This has led us to believe that deeper insights into chaotic behavior of a fluidized bed can be obtained by examining the fractal behavior of the time series.

One kind of fractal dimensions, among many defin-

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itions, can be obtained based on Hurst's rescaled range (R/S) analysis. This method was originally developed by Hurst (1956) and later used by many investigators (e. g., Mandelbort and Wallis, 1969, Fan *et al.*, 1990, Drahos *et al.*, 1992). A detailed description of this method has been given by Feder (1988). Let $Y(i)$ be a record containing τ readings uniformly spaced from time $i = t+1$ to time $t+\tau$, the average of this subrecord is given by

$$\langle Y(t) \rangle_\tau = \frac{1}{\tau} \sum_{i=1}^{\tau} Y(t+i) \quad (1)$$

Define $c(t, i)$ be the cumulative departure of $Y(t+y)$ from the mean, $\langle Y(t) \rangle_\tau$, for the subrecord between time $t+1$ corresponding to $y=1$ and time $t+i$ corresponding to $y=i$. This definition gives,

$$c(t, i) = \sum_{y=1}^i [Y(t+y) - \langle Y(t) \rangle_\tau] \quad (2)$$

The sample sequential range of $Y(t)$ for time lag τ is defined as

$$R(t, \tau) = \max_{0 < i \leq \tau} c(t, i) - \min_{0 < i \leq \tau} c(t, i) \quad (3)$$

and the sample sequential variance of $Y(t)$ is defined as

$$S(t, \tau) = \left[\frac{1}{\tau} \sum_{i=1}^{\tau} [Y(t+i) - \langle Y(t) \rangle_\tau]^2 \right]^{1/2} \quad (4)$$

The ratio, $R(t, \tau)/S(t, \tau)$, often called the rescaled range, is a random function with the scaling relationship (Mandelbort and Wallis, 1969, Feder, 1988)

$$\frac{R(t, \tau)}{S(t, \tau)} \propto \tau^H \quad (5)$$

where H is Hurst's exponent ranging from 0 to 1. According to Feder (1988), the local fractal dimension, D , can be related to H by $D = 2-H$. Physically, the fractal dimension D defined here describes the degree of a self-affine curve and the complexity of the system as well. In other words, a uniformly distributed time series generally raises the fractal dimension. Considering this property, we will attempt to relate the fractal dimension and the hydrodynamics of the fluidized beds.

2. Experimental

All the experiments were carried out in a cold fluidized bed made of Plexiglas of 0.1 m I. d. and 0.5 m in height. Air was passed through an oil filter and an orifice meter before entering the bottom of the bed. The superficial gas velocity was varied from 0.2 to 0.1 m/s to include the bubbling and turbulent fluidization regimes. Since particle entrainment became significant as the gas velocity was increased, a cyclone was installed on the exit of the bed to prevent particles (mostly fines) from escaping. Particles collected by the cyclone were returned to the lower density region simultaneously. In such a way, the

Fig. 1 Standard deviation, fractal dimension and solids holdup as a function of gas velocity for purely FCC particles ($x_c = 0$)

fraction of fine particles, which was accurately adjusted before experiments, was able to be kept nearly constant during the experiments. The properties of particles employed in this work are listed in Tables 1 to 3. The binary mixtures were formed with FCC as fine particles and silica sands as coarse particles. All experiments were performed at ambient temperature and atmospheric pressure with a total solid weight of 1.2 kg. Before each test, a desired fraction of coarse particles ranging from 0 to 100 wt% was carefully prepared.

In all tests, the absolute pressure was monitored from the pressure tap located on the wall 5 cm above the distributor. This tap was also connected to another pressure tap 5 cm above it to get the differential pressure signals. The absolute/differential pressure fluctuations were recorded with the aid of a real-time data acquisition system (Canopus Co. Ltd., Japan). This system consisted of a pressure transducer, an A/D converter (12 bit resolutions) and a NEC personal computer. The signals of time series of the pressure fluctuations were sampled with a frequency of 100 Hz and stored temporally in disks. The total acquisition time was 100 seconds, giving a total of 10000 data points. For each time series of pressure fluctuations, the standard deviation is calculated by

$$\sigma = \sqrt{\frac{1}{N} \sum (P_i - \bar{P})^2} \quad (6)$$

where $\bar{P}$ denotes the time-mean value of the pressure P_i over the sampling period. The gas velocity at which σ of pressure fluctuations peaks was then determined as the transition velocity U_c . As noted by Grace and Sun (1991), Chehbouni *et al.* (1994) and Bi and Grace (1995), U_c determined in such a way will be independent of the axial position of the pressure probe, representing the average U_c

Fig. 2 Standard deviation, fractal dimension and solids holdup as a function of gas velocity for FCC/silica sand-II binary particles ($x_c = 0.4$)

for the whole dense bed. Meanwhile, the solids holdup of the dense bed was calculated from the differential pressure measurement by

$$\epsilon_s = \frac{\Delta P}{\rho_p g \Delta z} \quad (7)$$

where the calculation of the bulk density of solids mixture can refer to Equation (10). For determination of the fractal dimension, the starting point t was selected as 1,500 and 1000, respectively. The values obtained in such a way were then used to yield an average of the fractal dimension for a given time series of pressure fluctuations.

3. Results and Discussion

Typical results are shown in **Fig. 1** for purely FCC particles ($x_c = 0$) and in **Fig. 2** for FCC/silica sand-II system ($x_c = 0.4$). It is seen that similar to the mono-density particles with relatively narrow size distribution (e. g., FCC particles), U_c in a binary solids fluidized bed can also be determined by the variation of the standard deviation of pressure fluctuations with gas velocity. This is seen by an increase in the standard deviation of pressure fluctuations with increasing gas velocity at $U < U_c$ due to the increase in bubble formation and bubble coalescence, and a decrease in the standard deviation of pressure fluctuations as larger bubbles begin to breakup at gas velocities higher than U_c . Similar results are also obtained for other fractions of coarse particles. From Figs. 1 and 2, we can also discover that the fractal dimension decreases at $U < U_c$ as the gas velocity is increased, reaches a minimum around U_c , and then increases with further increasing gas velocity. Based on the bubble interaction as suggested by the standard deviation,

Fig. 3 Typical pressure fluctuations ($x_c = 0$, $U_c = 0.48$ m/s). Gas velocities are changed from bubbling ($U_g = 0.3$ m/s) to turbulent fluidization ($U_g = 0.6$ m/s)

researchers have generally agreed that the heterogeneity of the gas-solids flow in the bed reaches a maximum at U_c (e. g., Chebouni *et al.*, 1994, Jin *et al.*, 1986, Cai *et al.*, 1989, Hashimoto *et al.*, 1988, Yang, 1988, Tsukada *et al.*, 1993). In other words, from the viewpoint of the standard deviation the heterogeneities of the bed may be equivalent under certain gas velocities before and after U_c . This is reflected by the similar pressure fluctuations, as shown in **Fig. 3**. Variation of the fractal dimension as shown in these figures, however, suggests that the degree of complexity of the gas-solids flow is relatively high before and after the regime transition. In other words, the gas-solids flow at the transition point is less complicated. Consider that there are strong bubble interactions in both the bubbling regime (dominated by formation, growing and coalescence) and the turbulent regime (dominated by breakup), which in turn result in dramatic turbulence of the emulsion phase. This fact will increase complexity of the gas-solids flow, thus rising the fractal dimensions. Increasing gas velocity in the turbulent fluidized bed or decreasing gas velocity in the bubbling fluidized bed, the small but rapid pressure fluctuations resulting from bubble interactions and dense phase turbulence lead to an increase in the fractal dimension, as noted in Figs. 1 and 2. At U_c , both bubble formation and breakup attain their maximum degrees, resulting in a maximum bubble size, and thus a

Fig. 4 Variation of fractal dimension with gas velocity for purely FCC, silica sand-I, silica sand-II particles

Fig. 5 Variation of fractal dimension with gas velocity for FCC/silica sand-II binary particles

relatively simple motion of bubbles, i. e., relatively vertical upward flow. Larger bubbles also lower the turbulence of the emulsion phase. Consequently, the fractal dimension reaches a minimum at U_c . All these findings are consistent with those reported in the literature. For example, van der Stappen *et al.* (1993) reported that the correlation dimension, another kind of fractal dimension, is about 4 to 5 for a freely bubbling fluidized bed (bubble diameter smaller than 0.05 m), and decreases to about 2 for a condition with less bubbles, but large diameter bubbles. When gas velocity is raised so that the bed enters fast or circulating fluidization, the correlation dimension is again increased to values of 3 to 5 (van der Stappen, *et al.*, 1994). Daw and Halow (1991) also found that the dimensionality in the slow bubble case is somewhat higher than for the slugging case, suggesting more complicated dynamics.

With respect to the solids holdup of the dense bed, one can find that in bubbling fluidized beds solids holdup changes insignificantly with gas velocity, but due to the significant entrainment of particles from the dense bed to the freeboard, the solids holdup of the dense bed decreases sharply with increasing gas velocity in the turbulent fluidization regime.

Fig. 6 Variation of transition velocity U_c with fraction of coarse particles x_c . Solid lines show results calculated by Eqns. (8) to (10)

The fractal dimensions obtained for purely FCC, silica sand-I and silica sand-II particles are plotted against the gas velocity in **Fig. 4**. It indicates that at a given gas velocity, the fractal dimension decreases when the particles become coarser or heavier due probably to the increased bubble size, reflecting the complexity of fluidization of fine particles. For the binary solids system, it is found that the fractal dimension generally decreases with increasing fraction of coarse particles x_c , while the positions where the fractal dimensions reach their minimum values (correspondingly, the standard deviations of the pressure fluctuations reach their maximum values) move to higher gas velocities as x_c is increased (**Fig. 5**).

It appears that fractal analysis offers a promising way to objectively classify flow patterns and to characterize the quality of fluidization. We expect that in addition to gas velocity and solids properties, the bed geometry and gas distributor might also influence the fractal dimension. Thus, further work in this direction will be continued in order to develop a deeper understanding of the flow mechanism and modeling the flow structure of fluidized beds.

The transition velocity, U_c , determined in this study is plotted against the fraction of coarse particles x_c in **Fig. 6**. It indicates that U_c increases with increasing x_c for both the FCC/silica sand-I and FCC/silica sand-II systems. Generally, U_c is found to be larger for the FCC/silica sand-II system than for the FCC/silica sand-I system. However, for the fines-rich flow (i.e., $x_c < 0.4$), the coarse particle diameter has less effect on the transition velocity U_c .

To develop a correlation that might give a proper prediction of U_c for binary solids systems, attempts have been made in this work. A few empirical correlations (Jin *et al.*, 1986, Cai *et al.*, 1989, Hashimoto *et al.*, 1988, Yang, 1988, Tsukada *et al.*, 1993) and theoretical approaches (Sun and Chen, 1989, Cai *et al.*, 1992) have been proposed to predict the transition velocity U_c in fluidized beds with the mono-density particles with relatively narrow size distribution. One of these approaches was developed by Cai and co-workers (1989) based on their extensive experimental studies (Jin *et al.*, 1986, Cai *et al.*, 1989, 1990, 1992). They

Table 1 Size distribution and key properties of FCC particles

d_{pi} (μm)	Acumulative fraction (wt%)
137.5	100.0
115.5	99.61
98.00	95.09
82.50	78.31
69.00	68.21
58.00	49.43
49.00	37.90
41.50	15.39
30.00	6.605
Particle density, ρ_p (kg/m ³)	1600
Mean particle diameter, d_p (μm)	52
Minimum fluidization velocity, (m/s)	0.00144
Terminal velocity, (m/s)	0.136

Table 2 Size distribution and key properties of silica sand-I particles

d_{pi} (μm)	Acumulative fraction (wt%)
460.0	100.0
385.0	99.82
300.0	99.19
213.5	95.29
163.0	51.31
127.5	30.50
97.00	4.216
81.00	2.007
63.50	0.8327
Particle density, ρ_p (kg/m ³)	2200
Mean particle diameter, d_p (μm)	166
Minimum fluidization velocity, (m/s)	0.02
Terminal velocity, (m/s)	1.21

carried out their experiments under different operating pressures (0.1 - 0.8 MPa) and temperatures (up to 773 K) for eight kinds of particles ($d_p = 53 - 1057 \mu\text{m}$, $\rho_p = 706\text{-}2580 \text{ kg/m}^3$, belonging to the A, B and D groups in Geldart's classification). For fluidized beds without internal baffles, a general correlation of transition velocity U_c (Cai *et al.*, 1989) is

$$\frac{U_c}{\sqrt{g d_p}} = \left(\frac{\mu_{20}}{\mu} \right)^{0.2} \left[K \left(\frac{\rho_{g20}}{\rho_g} \right) \left(\frac{\rho_p - \rho_g}{\rho_g} \right) \left(\frac{D_t}{d_p} \right) \right]^{0.27} \quad (8)$$

with

$$K = \left(\frac{0.211}{D_t^{0.27}} + \frac{0.00242}{D_t^{1.27}} \right)^{\frac{1}{0.27}} \quad (9)$$

A close agreement between experimental results from pressure fluctuation measurements and predictions based on the above equations has been confirmed recently by Bi and Grace (1995). To use Eqns. (8) and (9) to predict the transition velocity U_c of the binary solids fluidized beds, we introduce an equivalent particle diameter and an equivalent particle density, defined as

$$\begin{cases} d_p = \frac{1}{\frac{1-x_c}{d_{pf}} + \frac{x_c}{d_{pc}}} \\ \rho_p = \frac{1}{\frac{1-x_c}{\rho_{pf}} + \frac{x_c}{\rho_{pc}}} \end{cases} \quad (10)$$

Table 3 Size distribution and key properties of silica sand-II particles

d_{pi} (μm)	Acumulative fraction (wt%)
460.0	100.0
385.0	79.69
323.5	45.06
273.5	20.99
230.0	14.25
193.5	0.54
Particle density, ρ_p (kg/m ³)	2400
Mean particle diameter, d_p (μm)	338
Minimum fluidization velocity, (m/s)	0.09
Terminal velocity, (m/s)	2.59

In such a way, the transition velocity, U_c , for all the experimental conditions of this study is calculated and plotted in Fig. 6 as the solid lines. A fairly close agreement with the experimental results is clearly shown in this figure, although some overestimation occurs for the lower values of x_c (i. e., $x_c < 0.4$). The average error for all the experimental conditions is within 5%. Therefore, one can expect that the transition velocities U_c for binary solids fluidized beds could be properly estimated by combining Eqns. (8) to (10).

Conclusion

The hydrodynamic behavior of a binary solids fluidized bed has been investigated based on the measurements of pressure/differential pressure fluctuations. It appears that fractal analysis can be used as a tool to reveal the flow structure in the fluidized beds and to characterize the quality of fluidization. Large bubble motion at the transition velocity U_c leads to a less complicated gas-solids flow, while more and small bubble motion at fluidization conditions before and after the transition increase the complexity of the gas-solids flow. Experiments showed that addition of coarse particles will result in an increase in the transition velocity U_c . A correlation for predicting the transition velocity of a binary solids fluidized bed was also developed in this paper.

List of symbols

$c(t, i)$	= cumulative departure of time series from its mean	
D	= fractal dimension,	[-]
D_t	= riser diameter,	[m]
d_p	= particle diameter,	[m]
g	= gravitation acceleration,	[m/s ²]
H	= Hurst's exponent.	
K	= constant (see Eq. (9))	
N	= total sampling number	
U_c	= transition velocity from bubbling to turbulent fluidization,	[m/s]
U_g	= superficial gas velocity,	[m/s]
x_c	= fraction of coarse particles in the mixtures,	[wt%]
P_i	= pressure,	[Pa]
$\bar{P}$	= time-mean value of the pressure P_i over sampling period,	[Pa]
ΔP	= pressure drop,	[Pa]
$R(t, \tau)$	= sequential range	
$S(t, \tau)$	= sequential standard deviation	
t	= time lag	

t	= time	
Y	= time series	
y	= time lag	
Δz	= distance between two pressure taps	[m]

Greek letters

ε_s	= solids holdup of dense bed	
μ	= viscosity	[Pa.s]
ρ	= density	[kg/m ³]
σ	= standard deviation of pressure fluctuation	[Pa]

Subscripts

20	= priority at 20 °C
c	= coarse particles (silica sands)
f	= fine particles (FCC)
g	= gas
p	= particles

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