Study of transition velocities from bubbling to turbulent fluidization by statistic and wavelet multi-resolution analysis on absolute pressure fluctuations

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Abstract

Experiments were conducted in three circulating fluidized beds of 70 mm-i.d. $\times$ 2.2 m high, 108 mm-i.d. $\times$ 7 m high and 108 mm-i.d. $\times$ 5.75 m high (with an expanded top section of 1.5 m high) at ambient condition. The spent fluid cracking catalyst (FCC), glass beads and sand particles were taken as bed materials. The transition velocities U_c and U_k were analyzed by means of traditional statistic analysis and multi-resolution analysis (MRA) of wavelet analysis on the absolute pressure fluctuation (APF) signals acquired at different axial positions in the beds. According to the standard deviation of APF, the effects of axial positions and static bed heights on U_c and U_k were systematically investigated. An appropriate measuring interval of relative axial position was recommended to identify U_k and two correlations calculated by regression of data in literatures and this work were proposed to predict U_c and U_k for absolute pressure measurement. By means of MRA of wavelet analysis, a redefined variable, homogeneous index HI, deduced from the energy of SF and LF subsignals, was successfully applied to determine the U_c and U_k and demarcated the dynamic behaviors of Geldart group A (spent FCC) and group B (sand particles and glass beads) particles in the circulating fluidized beds.

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1. Introduction

Gas–solid fluidized bed system has been extensively employed in many industrial processes including mixing, drying, fluid catalytic cracking, coal combustion, gasification, etc. Among these processes, wide range of operating conditions is covered from the bubbling, the turbulent to the fast fluidization flow regimes among which the performance of fluidized beds is quite different. Thus, effective and exact discrimination of flow regimes is quite important and essential prior to any practical application. Yerushalmi et al. (1978) first proposed a quantitative criterion by means of relative fluctuations of pressure drop across the bed. They defined U_c , where the relative pressure fluctuations reach a maximum, as the onset velocity of the transition from bubbling to turbulent flow regime

and U_k as the onset velocity of turbulent flow regime where the relative pressure fluctuations decay from U_c and begin to level off. However, some researchers considered that the turbulent regime starts at U_c (Cai et al., 1990; Chehbouni et al., 1994; Chen and Bi, 2003; Grace and Sun, 1991; Kashkin et al., 2003; Lee and Kim, 1988; Makkawi and Wright, 2002; Rhodes, 1996, etc.). Also, inconsistent position of U_k exists in literatures. Rhodes and Geldart (1986) stated that U_k , at which a “reflux transport” is presented, is akin to choking velocity. U_k is affected by the position of pressure tapping and is considered to be strongly affected by the configuration and solids return system. Lee and Kim (1988) used the skewness and flatness of pressure fluctuations to determine the transition from bubbling to turbulent regime. They found the maximum point of flatness and the minimum point of skewness indicate the transition velocity U_c , however, U_k is not obtained in their studies. Bi and Fan (1992) found turbulent flow regime exists only for Geldart group A particles ($Ar < 125$) and U_k which marks the

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end of this regime decreases with the increasing of the column diameter. For Geldart group B and D particles ($Ar > 125$), U_k is equal to U_{tr} and does not change apparently with the column diameter. Chehbouni et al. (1994) stated that U_k is just an artifact due to using differential pressure measurement and turbulent flow regime starts then at U_c and ends at the U_{tr} . Recently, Makkawi and Wright (2002) demarcated U_c and U_k by means of electrical capacitance tomography (ETC) and elucidated that turbulent fluidization begins at U_c and ends at U_k . Nowadays, U_c is generally accepted as the onset gas velocity of turbulent fluidization; however, U_k is not a well-defined transition velocity and exists doubtfully.

Numerous tools had been presented—visual observation, capacitance probe, pressure probe, optical fiber probe and X-ray—to examine the transition velocities discriminating the different flow regimes in the fluidized beds. Among these tools, pressure fluctuation measurement by pressure probe was utilized most frequently and more suitable to industrial application. In addition, various kinds of analysis method on pressure fluctuations had been applied to examine the regime transitions, for instance, standard deviation, higher order moments (skewness and flatness), power spectral density function (PSDF), probability density function (PDF), chaos analysis and recent wavelet analysis. Although the amplitude (expressed in standard deviation) of pressure fluctuations was most commonly applied as an indicator of the state of fluidization, it alone was not sufficient to elucidate the composition of the fluctuating signals and to quantify the bed dynamics. A significant loss of information is inevitable if one just applies the standard deviation as an indicator of regime transitions (Dhodapkar and Klinzing, 1993). Power spectral density function examined the dominant frequency in pressure fluctuations which represented the frequency of bubbles/slugs or gas voids passing through the bed. However, deciding which peak in power spectrum is treated as a dominant frequency may be subjective (Johnsson et al., 2000). The definition of major frequency for the turbulent regime was rather difficult as its PSDF often spread widely. Thus, a combination of different kinds of analysis should be necessary and gave a better view of hydrodynamic behavior in fluidized beds.

In the last decade, wavelet transform has been widely applied to various engineering and scientific fields and discovered much useful information. However, only few attempts have so far been made for the multiphase flow system. Lu and Li (1999) indicated that wavelet filters the signals of pressure fluctuations in a bubbling fluidized bed and the scale 4 detail signal reflects the bubble behaviors. Ren and Li (1998) used wavelet transform to decompose the original pressure fluctuations into three scales corresponding to macro-scale, meso-scale and micro-scale in a circulating fluidized bed. The first one characterizes the effect of the processing unit on the system behavior, the second one describes the interaction of clusters or bubbles and the third one mainly characterizes particle motion in clusters or dilute phase. They verified that a fluidized bed exhibits multi-scale behaviors causing multi-resolution components in original time series. But how to diagnose the transition regime from pressure fluctuation signals was not presented in their results.

Park et al. (2001) used wavelet transform to obtain the approximation and detail signals of pressure fluctuations in a pressurized bubble column. They found the detail signals may directly relate to the bubble behaviors and their energies provide analogous information as the change of major frequency in Fourier power spectrum. Ellis et al. (2003) characterized the dynamic behaviors of void and dense phase in the turbulent flow regime by wavelet analysis on the local voidage fluctuation signals. They considered that the finer-scale details of the decomposed voidage signal are originated from the particle movement and the coarser-scale detail and approximations are mainly produced from the void movement. Furthermore, the statistical distribution (skewness and kurtosis) of these decomposed signals in the turbulent flow regime shows significant difference from that in the bubbling flow regime. Shou and Leu (2005a,b) successively characterized different flow regimes of fluid cracking catalyst (FCC) and sand particles in a circulating fluidized bed by the wavelet energy distribution of pressure fluctuating data. They further determined the transition velocities U_c and U_k by the method combining the power spectral density function and wavelet analysis of absolute pressure fluctuations.

So far the wavelet analysis has been considered as a powerful tool for investigating the signal with multi-scale components as well as the pressure fluctuations in the fluidized bed systems. In this study we attempted to examine the transition velocities U_c and U_k in circulating fluidized bed systems via traditional statistical analysis and multi-resolution analysis of wavelet transformation on the absolute pressure fluctuation signals. The effects of the axial position of pressure probe and the static bed height were also investigated. Multi-resolution analysis was formulated in order to relate the energy of wavelet multi-scales and the characteristic hydrodynamics in the fluidized beds with different kinds of bed materials. This methodology was expected to express better capability and higher flexibility on analyzing multi-scale structure from the bubbling to the turbulent flow regimes in the fluidized beds.

2. Experimental

Experiments were carried out in three circulating fluidized beds of 70 mm-i.d. $\times$ 2.2 m high (CFB-A), 108 mm-i.d. $\times$ 7 m high (CFB-B) and 108 mm-i.d. $\times$ 5.75 m high (CFB-C). The details of CFB-C were shown elsewhere (Shou and Leu, 2005a). Both CFB-A and CFB-B were made of transparent Plexiglas column equipped with an L-valve for returning the entrained particles, as shown schematically in Fig. 1. The perforated plates with free area of 3.02% (CFB-A) and 9.33% (CFB-B) were used as the gas distributor. Ambient air was supplied by Roots blower to fluidize the particles. The absolute pressure fluctuation signals were measured at different axial locations along the risers. To avoid the blockage by fine particles, all tips of the pressure probes were covered with screen of 400 mesh and were flushed with the inside wall of the risers. In each run of experiments, the discrete fluctuating data were recorded by an AD/DA card at a rate of 100 Hz and the total sampling time was 81.92 s. An S+ wavelet toolkit of the S-PLUS software was used to perform the wavelet transformation and multi-resolution

Fig. 1. Circulating fluidized beds (a) CFB-A: 7 mm-i.d. $\times$ 2.2 m high, (b) CFB-B: 108 mm-i.d. $\times$ 7 m high.

Table 1
Experimental conditions and properties of bed materials

Bed material	FCC	Glass beads	Sand
Geldart group	A	B	B
Mean particle size, d_p (μm)	78	159	194
Particle size range (μm)	0–160	105–210	177–210
Particle density, ρ_p (kg/m^3)	1880	2593	2635
Minimum fluidization velocity, U_{mf} (m/s) ^a	0.0045	0.025	0.038
Terminal velocity, U_t (m/s) ^b	0.27	0.98	1.26
Archimedes number, Ar	32.4	378	698
Static bed height, H_s (m)	0.4	0.4	0.4, 0.5, 0.6
Superficial gas velocity, U_o (m/s)	0.05–2.0	0.1–2.4	0.1–3.8

^aEstimated from Wen and Yu (1966).

^bEstimated from Haider and Levenspiel (1989).

decomposition. Table 1 lists the experimental operation conditions and the properties of particles employed as bed material in this study.

3. Data processing

3.1. Statistic analysis

For a given discrete pressure fluctuation signal $x(t)$, its standard deviation is defined mathematically as follows:

$$\sigma_x = \sqrt{\frac{1}{N-1} \sum_{t=1}^N (x(t) - \bar{x})^2},$$

where

$$\bar{x} = \frac{1}{N} \sum_{t=1}^N x(t). \quad (1)$$

A standard deviation of pressure fluctuations is generally regarded as a measure of bubble size and is extensively applied to mark the flow regimes. In Section 4.1 of this paper, the dependency of standard deviation on the superficial gas velocity in circulating fluidized beds was particularly discussed to determine the transition velocities from the bubbling to the turbulent fluidization under different operational conditions.

Fig. 2. Scaled and translated 4th-order “Symlet” wavelet.

3.2. Discrete wavelet transform

Wavelet transform is a relatively novel mathematical tool for signal processing. Similar to a windowed Fourier transform, a wavelet transform can measure the time-frequency variations of spectral components, but it provides more flexible time-frequency resolutions. The transform on a discrete signal can be carried out by discrete wavelet transform (DWT). The essence of DWT is to expand a signal, $x(t)$ ($t = 1, \dots, N$), as a sum of base functions $\phi_{j,k}(t)$ and $\psi_{j,k}(t)$. They are produced by dilations and translations of the orthogonal father wavelet function ϕ and the mother wavelet function ψ as follows:

$$\phi_{j,k}(t) = 2^{-j/2} \phi\left(\frac{t - 2^j k}{2^j}\right), \quad j, k \in I, \quad (2)$$

$$\psi_{j,k}(t) = 2^{-j/2} \psi\left(\frac{t - 2^j k}{2^j}\right), \quad j, k \in I, \quad (3)$$

where time shift $k = 1, 2, \dots, N/2^j$ and level $j = 1, 2, \dots, J$. J corresponding to scale 2^J of the base functions is the maximum level of wavelet transform and it is dependent on ϕ , ψ and N . Fig. 2 shows the dilated and translated forms of the Symlet wavelet. When j gets larger, the scale 2^j gets larger and the functions $\phi_{j,k}(t)$ and $\psi_{j,k}(t)$ become wider and spread out (Bruce and Gao, 1996). In this study, the fourth-order Symlet wavelet (sym4) was used as transform function to carry out DWT on pressure fluctuation signals. Thus, the wavelet transform of $x(t)$ can be obtained by

$$s_{J,k} = \int x(t) \phi_{J,k}(t) dt, \quad (4)$$

$$d_{j,k} = \int x(t) \psi_{j,k}(t) dt, \quad (5)$$

where $s_{J,k}$ and $d_{j,k}$ are called the approximation/smooth and detail coefficients, respectively. Roughly speaking, $s_{J,k}$ mainly represents the smooth behavior of $x(t)$ at the coarser scale and $d_{j,k}$ represents the detail part at the finer scale. The latter also provides the deviation between two successive scales of smooth coefficients $s_{j,k}$ and $s_{j-1,k}$. Consequently, $x(t)$ can be reconstructed by

$$x(t) \approx \sum_k s_{J,k} \phi_{J,k}(t) + \sum_k d_{J,k} \psi_{J,k}(t) + \sum_k d_{J-1,k} \psi_{J-1,k}(t) + \dots + \sum_k d_{1,k} \psi_{1,k}(t). \quad (6)$$

3.3. Multi-resolution analysis (MRA)

MRA decomposes the signal into orthogonal signal components which represent the components of $x(t)$ at different resolutions/scales. At each level j , the approximation signal $A_j(t)$ and the detail signals $D_j(t)$ can be obtained by the following:

$$A_J(t) = \sum_k s_{J,k} \phi_{J,k}(t), \quad J, k \in I, \quad (7)$$

$$D_j(t) = \sum_k d_{j,k} \psi_{j,k}(t), \quad j, k \in I. \quad (8)$$

Thus $x(t)$ is expressed in terms of these signals:

$$x(t) \approx A_J(t) + D_J(t) + D_{J-1}(t) + \dots + D_1(t). \quad (9)$$

Based on energy conservation, the total energy of $x(t)$ can be obtained by

$$E = \sum_{t=1, \dots, N} |x(t)|^2 = \sum_t |A_J(t)|^2 + \sum_t \sum_{j=1}^J |D_j(t)|^2, \quad (10)$$

the percentages of energy of $A_J(t)$ and $D_J(t)$ are defined as follows:

$$E_J^D = \frac{1}{E} \sum_{t=1}^N |D_J(t)|^2 \times 100\%, \quad (11)$$

$$E_J^A = \frac{1}{E} \sum_{t=1}^N |A_J(t)|^2 \times 100\%. \quad (12)$$

So, the energy distribution of $x(t)$ can be obtained by calculating Eqs. (11) and (12) under various levels.

4. Results and discussion

4.1. Statistic analysis on pressure fluctuations

Fig. 3 shows the dependency of the standard deviation of absolute pressure fluctuations on superficial gas velocity for FCC and glass bead particles with pressure probes located at different axial positions ($z = 0.1$ – 0.8 m). As gas velocity was increased in bubbling flow regime, the standard deviation increased rapidly due to coalescence of small bubbles into large bubbles/slugs. The transition velocity U_c , corresponding to the gas velocity at which the standard deviation reached a maximum, was plainly detected at each position in the beds. Over U_c , large bubbles/slugs gradually erupted into small gas voids which fast coalesced and split alternately. Fine particles were elutriated from the bed and the amount of particles in the free-board zone increased with the increase of the gas velocity. Thus, the level of dense bed surface decreased and became more and more fuzzy. These phenomena led to attenuation in amplitude and rise in the oscillation frequency of pressure fluctuations in the beds. As gas velocity was further increased, the standard deviation was found to level off to a plateau. The critical velocity U_k , after which the change of the standard deviation was not obvious or became much smoother with increasing gas velocity, was obtained from the intersection of the extended lines of the attenuation and the plateau parts. Table 2 summarizes the transition velocities U_c and U_k obtained from absolute pressure fluctuation measurement and the corresponding experimental conditions in literatures. No doubt the transition velocity U_c can be specified by all of the authors listed in Table 2; however, U_k is not always found. The influence of particle size d_p , density ρ_p , and riser bed diameter D_t on U_c and U_k have been widely discussed by authors (Bi et al., 2000; Bi and Fan, 1992; Cai et al., 1989; Ellis et al., 2004; Rhodes and Geldart, 1986; Yerushalmi and Cankurt, 1979; Zhao and Yang, 1991, etc.). However a systematic investigation about the effects of axial position of pressure probe z and static bed height H_s on U_c and U_k obtained from absolute pressure fluctuations is still lacking. In the following sections, the effects of z and H_s had been appropriately discussed.

4.1.1. U_c and U_k at different axial positions

As shown in Fig. 3, U_c was almost independent of axial positions from the gas distributor for both FCC and glass bead particles. However, U_k decreased slightly with heightening the

Fig. 3. Standard deviation of absolute pressure fluctuations at different axial positions: (a)–(f) FCC, $z = 0.1$ – 0.8 m, $H_s = 0.4$ m, (g)–(l) glass beads, $z = 0.1$ – 0.8 m, $H_s = 0.4$ m in CFB-A.

Table 2
Summary of transition velocities U_c , U_k by absolute pressure fluctuation measurement and the corresponding operation conditions in literature

Reference	Properties of bed material		D_t (m)	H_s (m)	z (m)	U_o (m/s)	U_c (m/s)	U_k (m/s)	Analysis method	Comments
	d_p (μm)	ρ_p (kg/m^3)								
Satija and Fan (1985)	Glass beads		0.102	0.15 ^a	0.152 ^a	40–3.92	2.24	a	rms of PF	U_o may be too small to identify U_k ; the exact position of probe and H_s are not clearly indicated
	232	3537		0.363	0.303	0.56–6.85	2.73	a		
	550	3537				1.10–6.85	4.29	a		
	696	3537				1.10–6.85	5.06	a		
Jin et al. (1986)	Silica gel		0.28	0.62	Middle	0.08–1.0	0.67	a	Non-uniformity coef. in time domain, F_p	The choice of dominant frequency used to calculate F_p is somewhat difficult especially in turbulent flow regime
	566	1330					0.85	a		
	52.7	1667					0.55	a		
	65.3	1172					0.42	a		
Lee and Kim (1988)	Glass beads		0.10	1.00	~ 0.53	0.12–1.28	0.84	a	s.d. of PF	The recycle of entrained solid particles may be too high. Besides, an obvious plateau can be found at $U_o = 0.94 \text{ m/s}$
	56	729				0.4–2.2	0.44	1.26	s.d. of PF	U_k listed here is taken as U_{k1} in their study
	78	2400		0.7		0.3–3.2	1.20	2.10		
	134	2400		0.7		0.3–4.4	1.40	2.30		
Son et al. (1988)	430	2630	0.38	6.0	0.2	0.25–2.5	1.10	a	Mean PF	
Judd and Goosen (1989)	Ferrosicicon powder A		0.14	1.5	0.02	0.12–0.84	0.70	a	s.d. of PF	The pressure signals just above the distributor may be affected by gas jetting
	56	729				0.4–2.2	0.44	1.26	s.d. of PF	
	78	2400		0.7		0.3–3.2	1.20	2.10		
	134	2400		0.7		0.3–4.4	1.40	2.30		
Sun and Chen (1989)	Amoxidation catalyst		0.1	1.0–2.0	0.5	0.1–0.6	0.60	a	Mean amplitude of PF	
	54	1800					0.40	a		
	54	1800					0.40	a		
	64	1800					0.55	a		
Cai et al. (1990)	28	706	0.139	a	In dense bed	0.1–1.0	0.60	a	Average amplitude of PF	H_s and z are not clearly indicated
Leu et al. (1990)	Sand		0.108	a	a	0.25–2.75	1.05	1.67	s.d. of PF	H_s and z are not clearly indicated
	90	2600								
Horio et al. (1992)	FCC		0.05	~ 1.0	0.53	0.1–1.6	0.50	0.60	rms of PF	
	60	1000								
Tsukada et al. (1993)	Sand		0.05	0.16–0.20	0.08	0.4–4.0	1.50	3.50	rms of PF	
	106	2600								
Tsukada et al. (1993)	FCC		0.05	0.16–0.20	0.08	0.10–1.03	0.30	0.65	rms of PF ($P = 0.1 \text{ MPa}$)	
	46.4	1780								

Table 2 (Continued)

Reference	Properties of bed material			D_t (m)	H_s (m)	z (m)	U_o (m/s)	U_c (m/s)	U_k (m/s)	Analysis method	Comments
	d_p (μm)	ρ_p (kg/m^3)									
Chehbouni et al. (1994)	FCC	78	1450	0.082	0.45	0.05	0.1–1.1	0.26	a	s.d. of PF	The z of probe is too low or somewhat too high; the use of bubble cap distributor may produce bubbles of lower speed that cause the transition of flow regimes smoother
	Sand	130	2650			0.45	0.1–3.0	0.26	a		
						0.05		0.75	a		
Bi and Grace (1995)	FCC	60	1580	0.102	0.60	0.20	0.1–1.5	0.75	a	s.d. of PF	The use of expanded-top fluidized bed keeps significant amount of particles in the freeboard at higher U_o , thus the s.d. of PF persistently decrease with increasing U_o
						0.35		0.70	a		
						0.45					
Cui et al. (2000)	FCC	70	1673	0.152	0.30	0.15	0.16–2.0	0.70	a	Dimensionless s.d. of PF	There is only a transition velocity U_c in such a shallow bed ($H_s/D_t < 2$)
						0.28		0.70	a		
						0.41		0.57	a		
Kashkin et al. (2003)	Sand	385	2650			0.20		0.52	0.90 ^b	s.d. of PF	Expanded-top fluidized bed is used; though majority of entrained particles are effectively returned to the bottom dense bed at higher U_o , increase of particles kept in freeboard may reduce the magnitude of pressure fluctuations in dense bed
	Alpha-alumina	50	2100	0.15	0.50	0.16	0–1.25	0.43	0.96 ^b		
						0.26		0.77	a		
Shou and Leu (2005a)	FCC	71	1800	0.108	0.50	0.36	0.3–2.5	0.70	1.65	s.d. of PF	Expanded-top fluidized bed is used; though majority of entrained particles are effectively returned to the bottom dense bed at higher U_o , increase of particles kept in freeboard may reduce the magnitude of pressure fluctuations in dense bed
						Plenum		1.00			
Shou and Leu (2005b)	Sand	323	2635	0.108	0.30	0.14	0.3–3.2	1.15	a	s.d. of PF	
						0.30		1.18	a		
						0.50		1.15	a		
						0.14		1.60	a		
						0.30		1.40	a		
						0.50		1.40	2.35 ^b		

^aNot specified.
^bAmbiguous.

axial position of pressure probe and was only detected at the specific axial positions (see Figs. 3(c) and (d) for FCC and Figs. 3(h)–(k) for glass beads). This result differed from the

result of [Chehbouni et al. \(1994\)](#) who proposed that U_k cannot be found by using absolute pressure fluctuation measurement and is only detected by means of differential pressure transducer. Based on our observation, beyond U_c , increasing the superficial gas velocity would lead the level of bed surface (i.e. the interface between the dense bed and the splash zone) to drop downward. Meanwhile, the standard deviation of the absolute pressure fluctuations attenuated gradually. As further increasing the gas velocity, more and more solid particles were entrained into the splash zone. Then the level of bed surface dropped below the pressure probe and exposed it to the splash zone. The variance of the standard deviation consequently became smoother. In such case, the pressure probe at higher axial position was exposed to the splash zone earlier than that located at lower axial position. Therefore, a lower value of U_k was obtained at higher position. [Rhodes and Geldart \(1986\)](#) also found that U_k decreases with increasing the distance of the upper pressure tapping from the distributor, though differential pressure fluctuation (DPF) measurement was used in their study. To further verify the above contention, the change of dense bed height of FCC

Fig. 4. Dense bed height versus superficial gas velocity for FCC in CFB-A.

Fig. 5. Standard deviation of absolute pressure fluctuations at different axial positions for sand particles in CFB-B: (a) $H_s = 0.4$ m, (b) $H_s = 0.5$ m, (c) $H_s = 0.6$ m.

Fig. 6. (a) Standard deviation of APF versus solid hold-up, (b) solid hold-up versus superficial gas velocity for FCC particles.

particles with the superficial gas velocity was observed virtually, as shown in Fig. 4. When the superficial gas velocity was increased from 0.6 to about 0.97 m/s, the height of dense bed surface H_d then gradually decreased from its maximum value to 0.4 m. Further increasing the superficial gas velocity to about 1.05 m/s, H_d would decrease to around 0.3 m, as indicated by the vertical arrows in Fig. 4. The superficial gas velocities of 0.97 and 1.05 m/s were well consistent with U_k depicted in Figs. 3(c) and (d), respectively. Thus, U_k was preferentially detected by the pressure probe located at higher positions in the dense bed. In other words, when the pressure probe was located near the gas distributor or in the splash zone/freeboard during the whole range of operation, the transition velocity U_k was difficult to be detected, as shown in Figs. 3(a), (b), (e) and (f) for FCC and Figs. 3(g) and (l) for glass beads.

The same result was also confirmed for sand particles in Figs. 5(a)–(c) which showed the standard deviation of absolute pressure fluctuations obtained at different axial positions in the CFB-B system with 0.4, 0.5 and 0.6 m of static bed height (H_s),

Fig. 7. Standard deviation of APF versus solid hold-up for sand particles.

Table 3
Transition velocities U_c and U_k determined by statistic analysis

Bed material	H_s (m)	z (m)	U_c (m/s)	U_k (m/s)
FCC	0.4	0.10	0.54	a
		0.20	0.54	a
		0.30	0.54	1.11
		0.40	0.55	0.94
		0.60	0.52	0.90 ^b
		0.80	0.63	a
Glass beads	0.4	0.10	0.86	a
		0.20	0.85	1.62
		0.30	0.86	1.52
		0.40	0.86	1.45
		0.60	0.72	1.53
		0.80	0.86	a
Sand	0.4	Plenum	1.22	1.86 ^b
		0.10	1.22	1.82 ^b
		0.30	1.22	1.82
		0.40	1.22	1.78
		0.60	1.15	1.72
	0.5	0.10	1.29	2.25 ^b
		0.25	1.24	2.08
		0.40	1.25	1.90
		0.60	1.29	1.85
	0.6	0.10	1.50	2.85 ^b
		0.30	1.48	2.83 ^b
		0.50	1.58	2.70 ^b
		0.70	1.58	2.68 ^b

^aNot found.
^bAmbiguous.

respectively. As well as FCC and glass beads in the CFB-A, the U_c of sand particles could be detected easily from each peak value of fitting curve; however, U_k in the plenum or the lowest axial position ($z = 0.1$ m) was somewhat ambiguous. Even an obvious plateau was observed for each of these measuring positions at much higher gas velocity (about 3.1–3.3 m/s); we would like to refer this condition to significant entrainment of sand particles from the riser bed rather than the indication of

Fig. 8. Comparison of original pressure fluctuations ($z = 0.1$ m) and its PSDF in CFB-B for sand particles with different static bed heights ($H_s = 0.4, 0.5$ and 0.6 m): (a) time domain, (b) frequency domain.

U_k . Similar trend was also observed in Fig. 3(l) for glass beads at $U_o = 1.8$ m/s. Beyond this superficial gas velocity, the magnitude of APF began to decrease to an extremely small value which was almost identical with that in an empty bed, so U_k was not found in this case. In addition, the gas velocities cor-

responding to the above condition for different axial positions and static bed heights were quite close to each other and were well consistent with the blow-out velocity, U_{se} (3.13 m/s for sand particles and about 1.7 m/s for glass beads), proposed by Bi et al. (1995).

Fig. 9. Transition velocities U_c and U_k at different axial positions for (a) FCC and (b) glass bead particles.

Further insight of the regime transition at different axial positions could also be characterized by the relationship between the standard deviation of pressure fluctuations and the corresponding solid hold-up (ε_s). Bai et al. (1996) investigated the standard deviation of DPF against the corresponding ε_s at various experimental conditions. They demonstrated that the standard deviation of DPF increases with the decrease of ε_s from the minimum fluidization to the transition velocity U_c (where $\varepsilon_s = 0.35$), followed by a sharp decrease of standard deviation with decrease in the ε_s till the critical velocity between the turbulent and the fast fluidization regimes (where $\varepsilon_s = 0.15$). A relatively small decreasing rate of standard deviation with decrease of ε_s preserves until the pneumatic transport regime is approached (where $\varepsilon_s < 0.05$). To discover the influence of axial position on the transition velocities U_c and U_k , the dependency of standard deviation of APF on the corresponding ε_s , deduced by the mean pressure drop, was presented for FCC and sand particles in this study. Fig. 6(a) shows the standard deviation of APF at $z = 0.2$ and 0.5 m against ε_s for FCC particles in the CFB-C system. This diagram indicates that the peak values of

standard deviation of APF (where $\varepsilon_s = 0.32$) measured at the upper ($z = 0.4$ m) and the lower ($z = 0.1$ m) positions of dense bed were almost the same and the corresponding gas velocity was close to the U_c determined by the standard deviation of APF versus the riser gas velocity. It implied that U_c was almost not affected by the axial positions of APF measurement. When the gas velocity was continuously increased to 1.18 m/s, the flow pattern observed at the upper position began to change from the turbulent to the fast fluidization flow regime, since the corresponding $\varepsilon_s = 0.14$ approached the critical solid hold-up between the turbulent and the fast fluidization as suggested by Bai et al. (1996). Simultaneously, the flow pattern at the lower position still maintained in the turbulent fluidization flow regime with $\varepsilon_s = 0.24$. Besides, the ε_s at the lower position was somewhat larger than that at the higher position between U_o ranged from 1.00 to 1.45 m/s, as shown in Fig. 6(b). The superficial gas velocities, $U_o = 1.1$ m/s at $z = 0.5$ m and $U_o = 1.36$ m/s at $z = 0.2$ m, beyond which the ε_s suddenly dropped were almost identical with the points where the standard deviation of APF began to level off in Fig. 6(a). This velocity was consequently regarded as U_k . The same result could also be found for the sand particles, as shown in Fig. 7. This figure indicates that there was an obvious leveling-off of standard deviation as the ε_s of sand particles decreased from 0.3 to 0.1 and the gas velocity corresponding to the critical solid hold-up ($\varepsilon_s = 0.19$) was quite close to U_k determined from Fig. 5(b) by standard deviation of APF. Summarizing these results we could conclude that:

- Regime transition from turbulent to the fast fluidization happened earlier at the upper axial position, as well as mentioned by Rhodes and Geldart (1986), then developed downward in the dense bed.
- The leveling-off of the standard deviation of APF at U_k corresponding to the regime transition was mainly attributed to the sudden decrease of solid hold-up at the observation position, in other words, U_k was apparently related to the variation of mean solid hold-up around the pressure probe and could be identified as the pressure probe was exposed from the dense phase to the relatively dilute phase.

Table 3 summarizes the transition velocities U_c and U_k determined from Figs. 3 and 5. For FCC and glass bead particles with constant static bed height, U_c showed almost independent with the axial positions along bed height as similar results observed in literatures (Bi and Grace, 1995; Chehbouni et al., 1994; Chen and Bi, 2003; Rhodes and Geldart, 1986; Shou and Leu, 2005a). However, U_k decreased slightly with heightening the axial position, as discussed above. For sand particles in CFB-B system, U_c also did not change significantly with axial position (Chehbouni et al., 1994; Shou and Leu, 2005b) and U_k followed the same trend as FCC and glass beads in CFB-A system.

4.1.2. Effect of static bed height on U_c and U_k

In addition to the axial position, the static bed height was also found evidently to affect the U_c and U_k . Rhodes and Geldart (1986) found that U_c slightly increases from 1.1 to 1.2 m/s

Fig. 10. Transition velocities U_c and U_k at different axial positions for sand particles with (a) $H_s = 0.6$ m, (b) $H_s = 0.5$ m, (c) $H_s = 0.4$ m.

Fig. 11. Correlation for Re_c in terms of Archimedes number.

and U_k increases from 1.7 to 2.33 m/s, as the static bed height varies from 0.2 to 0.9 m. These data were obtained from a 76 mm-i.d. $\times$ 4 m high column with 69 μ m sand particles as

bed material. Zjierveld et al. (1998) observed that bubbles/slugs coalesce and grow for a longer time for deeper beds by chaos analysis. On the other hand, slugs are partly broken up easier

Fig. 12. Correlation for Re_k in terms of Archimedes number.

for the shallow bed as gas velocity was beyond 2 m/s. Ellis et al. (2004) studied the dependency of U_c of FCC particles on the aspect ratio H_s/D_t . At constant elevation, a significant increase of U_c with increasing static bed height ($H_s = 0.6$ – 1.5 m) is also presented in their data.

The transition velocity U_c is well known as the gas velocity at which bubbles/slugs grow to a maximum size and begin to collapse into smaller bubbles/voids. In our experimental observation, the big bubbles/slugs quickly formed and persisted for higher gas velocity on increasing the static bed height. Thus, the breakup of big bubbles/slugs was delayed especially for $H_s = 0.6$ m of sand particles. Fig. 8 shows the pressure fluctuations for different static bed heights of the sand particles and the corresponding PSDF at the same measurement position ($z = 0.1$ m) and approximately with the same gas velocity. Saw-toothed pressure wave caused by big bubbles/slugs was measured clearly for higher static bed height; however, the breakup of big bubbles/slugs already began for lower static bed height as small and high-frequency pressure fluctuations were observed interweaving among the large ones. This phenomenon also directly projected on the PSDF of pressure fluctuation signals. As shown in Fig. 8(b), the bandwidth of PSDF became wider as the static bed height decreased and some minor frequencies appeared at higher values. It provided the evidence that bubbles/slugs collapsed earlier for the lower static bed height thus caused U_c to decrease with decreasing static bed height. Besides, the decrease of U_k can be contributed to the descent of interface between dense bed and splash zone as the static bed height is decreased (Mori et al., 1992). Lower level of interface exposed the pressure probes in the splash zone at lower gas velocity, thus a smaller value of U_k was obtained.

4.1.3. The choice of appropriate measurement location

According to the above discussion, different flow patterns could be observed at different axial positions in the fluidized beds. The transition velocities between different flow regimes were affected by both static bed height and axial position of pressure probe. Thus, an appropriate measurement location should be necessary in order to accurately detect the regime

transition. Figs. 9(a) and (b) show the relative axial position (z/H_s), defined as the ratio of the axial position of probe above the gas distributor to the static bed height, versus transition velocities U_c and U_k of FCC and glass beads. The result showed that U_c of both FCC particles and glass beads showed no obvious change with z/H_s ; however, U_k decreased with increasing z/H_s except at $z/H_s = 1.5$ where the eruption of bubbles/slugs was considerably violent for glass beads. Besides, no U_k was identified at the highest measuring position ($z/H_s = 2.0$ for FCC and glass beads) where the pressure probe was exposed to the splash zone during the whole experimental run. On the other hand, U_k at the lower measuring portion of the bed ($z/H_s < 0.5$), where the flow pattern was mostly affected by the structure of gas distributor, gas jetting or solid reflux system, was usually not found or ambiguous. Similar trend was also obtained for sand particles as shown in Fig. 10. Some recommendations about the measuring positions had been given by other authors. Brereton and Grace (1992) suggested that the pressure probes should be immersed below the surface of bottom dense bed at all time to avoid the region where bubbles/slugs erupt when using instantaneous differential pressure measurement. Bi and Grace (1995) also recommended keeping away the pressure measurements from the bed surface for avoiding the apparent transition. It was worthy to note that in Table 2, some of the authors, who had the pressure probes located approximately between 0.5 and 1.0 of z/H_s , were able to identify U_k (Horio et al., 1992; Mori et al., 1988; Tsukada et al., 1993). On the contrary, no U_k was determined by the authors who had the pressure probes located at relatively lower positions (Bi and Grace, 1995; Kashkin et al., 2003; Shou and Leu, 2005a,b; Son et al., 1988; Sun and Chen, 1989) or just above the gas distributor (Chehbouni et al., 1994; Judd and Goosen, 1989). Based on the data from Table 2 and this study, an appropriate position of absolute pressure fluctuation measurement for identifying transition velocity U_k was consequently considered between 0.5 and 1.0 of relative axial position z/H_s . Nevertheless, there were still some authors (Bi and Grace, 1995; Chehbouni et al., 1994; Kashkin et al., 2003; Lee and Kim, 1988; Shou and Leu, 2005a,b) who carried out the APF measurements in the interval ($0.5 < z/H_s < 1.0$) did not detect any

Fig. 13. Multi-scale subsignals of absolute pressure fluctuations and their PSDs for FCC: (a) $U_o=0.14$ m/s, (b) $U_o=0.55$ m/s, (c) $U_o=0.83$ m/s in CFB-A, $H_s=0.4$ m, $z=0.2$ m.

Fig. 13. (continued).

Fig. 14. Energy plot of SF, LF and DC subsignals for FCC in CFB-A, $H_s = 0.4$ m, $z = 0.2$ m.

U_k . The reason was probably related to the structures of experimental apparatus (e.g. expanded-top section, bubble cap gas distributor, position of solid particles recycled back to the riser, etc.) employed by these authors. Further future works should be done in order to verify the inference.

The transition velocity U_k obtained between 0.5 and 1.0 of z/H_s ($H_s = 0.4$ m for FCC particles and glass beads; $H_s = 0.4$

and 0.5 m for sand particles) were averaged and taken in comparison with the literature data in Table 2. For the sand particles, the U_c and U_k of $H_s = 0.6$ m showed a significant deviation from those of $H_s = 0.4$ and 0.5 m owing to the formation of serious slugging flow, thus, they were excluded from the data regression. In Figs. 11 and 12 the dependency of Re_c and Re_k of these data on the Archimedes number was shown. The correlation equations calculated for these data were expressed as follows:

$$Re_c = 0.837Ar^{0.487} \quad (0.562 < Ar < 43270, 0.05 < D_t < 0.80 \text{ m}), \quad (13)$$

$$Re_k = 1.174Ar^{0.481} \quad (6.45 < Ar < 3220, 0.05 < D_t < 0.108 \text{ m}). \quad (14)$$

As shown in the figures, Re_c and Re_k obtained from this study showed good agreement with the correlation equations. The equation proposed by Bi et al. (2000) for predicting U_c with APF measurement was also given in Fig. 11. The Re_c predicted from Eq. (13) was a little higher than that predicted by Bi et al.'s equation. It was probably because they introduced some transition velocities, determined from the dimensionless standard deviation of APF, into curve fitting, hence lower values of U_c were obtained. On the other hand, Eq. (14) showed only a little difference in comparison with the correlation

Fig. 15. Homogeneous index versus superficial gas velocity for (a) FCC, (b) glass beads in CFB-A with $H_s = 0.4$ m, $z = 0.2$ m.

equations proposed by Horio (1986) and Perales et al. (1991) for Geldart A and B group particles, respectively.

4.2. Wavelet analysis on pressure fluctuations

4.2.1. Multi-scale analysis on pressure fluctuations

In this study, the pressure fluctuation data were separated into three specific scales of subsignal by resorting to wavelet multi-resolution decomposition as introduced in Sections 3.2 and 3.3. They were the micro-scale corresponding with higher frequency and small fluctuations (SF), meso-scale corresponding with intermediate frequency and large fluctuations (LF) and macro-scale corresponding with lower frequency (DC). Here the SF subsignal is defined as follows:

$$SF = \sum_{j=1}^m D_j(t), \quad (15)$$

where $m = 4$ in this work. The SF subsignal represents a hybrid of details of original signal $x(t)$ below level m and has an approximate frequency interval $[50/2^4, 50]$ Hz. It mainly captures

the fluctuations contributes from small and rapid bubbles/voids. And the definition of LF is given by

$$LF = \sum_{j=m+1}^J D_j(t), \quad (16)$$

where $J = 7$ is the maximum decomposition level set in this study. The LF subsignal with approximate frequency interval $[50/2^7, 50/2^4]$ Hz captures the behavior of large bubbles/voids or slugs. The residual part, DC subsignal, equals to $A_J(t)$ with approximate frequency interval $[0, 50/2^7]$, indicates the intensity of moving-average in the original fluctuation signal.

Figs. 13(a)–(c) show the original absolute pressure fluctuations and its three scales of subsignal obtained from multi-scale analysis of wavelet transform for FCC particles at 0.14, 0.55 and 0.83 m/s of superficial gas velocities, respectively. The corresponding PSDF was also applied for each scale of subsignal to estimate their frequency contents. In the bubbling flow regime, the LF subsignal (the middle top of Fig. 13(a)) mainly captured the large fluctuations caused by relatively large bubbles which had a major frequency about 1.2 Hz. The small fluctuations interweaving in LF subsignal was mostly captured by the SF subsignal (the middle center of Fig. 13(a)) which had a higher major frequency about 4 Hz and it was probably produced by passage of small bubbles and interstitial gas void near the pressure probe or the slight oscillations of bed surface. Further increasing superficial gas velocity, bubbles were promoted to coalesce larger and it caused the increasing in the amplitude of LF subsignal, as shown in Fig. 13(b). On increasing superficial gas velocity beyond U_c of FCC particles, the large bubbles/slugs erupted into small voids that induced decreasing in amplitude of LF subsignal, as shown in Fig. 13(c). In this flow regime, higher degree of turbulence was observed, the coexistence of the burst of slug-like behavior and the fast-fluidization-like motion, as mentioned by Brereton and Grace (1992), could also be captured by the LF and SF subsignals.

4.2.2. Homogeneous index

To understand the relationship between multi-scale subsignals and change of flow regimes, the energies of the three subsignals were calculated under different superficial gas velocities, as shown in Fig. 14. With increasing superficial gas velocity ($U_o < 0.55$ m/s) in bubbling/slugging flow regime, the energy of LF subsignal gradually increased due to the coalescence of small bubbles into big bubbles/slugs. Meanwhile, the energy of SF subsignal decreased in the opposite direction. In other words, the formation of big bubbles/slugs would cause the energy content of pressure fluctuation signals to transfer from the smaller scale to the larger scale subsignal. When the flow pattern was shifted to turbulent fluidization ($U_o > 0.55$ m/s) by further increasing the superficial gas velocity, the energy of LF subsignal attenuated due to the breakdown of big bubbles/slugs into small gas voids. On the contrary, the energy of SF subsignal increased until large bubbles/slugs were diminished and substituted by irregular gas voids. A competition, therefore, was observed between the energy of LF and SF subsignals as the flow regime change. In this sense, we defined a variable,

Fig. 16. Homogeneous index versus superficial gas velocity for $H_s = 0.4$ m with (a) FCC, $z = 0.1$ m, CFB-A, (b) FCC, $z = 0.4$ m, CFB-A, (c) glass beads, $z = 0.1$ m, CFB-A (d) glass beads, $z = 0.4$ m, CFB-A, (e) sand, $z = 0.1$ m, CFB-B, (f) sand, $z = 0.4$ m, CFB-B.

called homogeneous index (HI), determined by the energy ratio of the SF and LF subsignals, to characterize the transition of flow regimes. Its definition is given as follows:

$$HI \equiv \frac{\text{energy of SF}}{\text{energy of LF}} = \frac{E_{SF}}{E_{LF}} = \frac{\sum_{j=1}^4 D_j^2(t)}{\sum_{j=5}^7 D_j^2(t)}. \quad (17)$$

4.2.3. Determine U_c and U_k by HI

Figs. 15(a) and (b) show the dependency of HI upon the superficial gas velocity for FCC and glass beads, respectively. Four different regions (at least three regions for FCC) can be distinguished in the diagrams. Regions I and II represented the bubbling/slugging flow regime; region III represented the turbulent flow regime and region IV was the fast fluidization flow regime. In region I, bubble coalescence dominated and bubble size increased with increasing gas velocity causing attenuation of HI. Near the end of region I, for glass beads, bubbles enlarged rapidly to a stable maximum size which was only subject to the diameter of bed (Chen and Bi, 2003), large squared-nose slugs appeared and existed for a wide range of gas velocity as the region II shown in Fig. 15(b). The corresponding HI kept in a low value and did not vary apparently till the slugs began to breakup at higher gas velocity. However, for FCC particles, the stable maximum bubble size was small (usually less than 10 cm) and clear slugs were not observed (Mori et al., 1988). The bubbles appeared to split and coalesce frequently, so that the HI decreased monotonously to a minimum and then increased immediately with increasing gas velocity into region

III. Thus, region I was difficult to be differentiated from region II for fine particles. Following region II was region III after which large slugs began to collapse. In region III there was a progressive extinction of large bubbles/slugs and augmented formation of small gas void inside the bed causing increasing of HI. The homogeneity kept increasing with superficial gas velocity until large bubbles/slugs completely disappeared. Hereafter, HI leveled off and the flow regime gradually changed from the turbulent to the fast fluidization.

Cooperating the above discussion and statistic analysis in Section 4.1, the transition velocity U_c could be marked as the superficial gas velocity after which HI began to increase obviously, i.e. the interface between regions II and III, the big bubbles/slugs began to collapse hereafter. The corresponding gas velocity at the interface between regions II and III was approximately equal to the U_c obtained from standard deviation of absolute pressure fluctuations (Figs. 3(b) and (h)). And the approach to the U_k for FCC particles was accompanied by the gas velocity at which the HI began to level off after a gradual increase, i.e. the interface between regions III and IV. While U_k for glass beads and sand particles could be identified by the gas velocity at which the HI reached to a maximum. Furthermore, the minimum slugging velocity, U_{ms} , could only be found for glass beads and sand particles. It was located by a sudden change of HI at the interface of regions I and II. Beyond U_{ms} , the HI did not change obviously due to the maximum stable bubble size had been developed. For FCC particles, bubbles are considered unable to grow to be of comparable size

Fig. 17. Homogeneous index versus superficial gas velocity at $z=0.1$ m with different H_s of (a) 0.6 m, (b) 0.5 m, (c) 0.4 m for sand particles.

Fig. 18. Homogeneous index versus superficial gas velocity at $z=0.4$ m with different H_s of (a) 0.6 m, (b) 0.5 m, (c) 0.4 m for sand particles.

to the column diameter (Grace and Bi, 1997). Thus, no significant transition between regions I and II was marked from the HI diagram.

4.2.4. Effect of axial position on HI

Fig. 16 shows the homogeneous index versus superficial gas velocity near the bottom ($z=0.1$ m) and the top ($z=0.4$ m) of dense bed for FCC, glass beads and sand particles. For FCC particles with pressure tap at $z=0.1$ m (Fig. 16(a)), U_c and U_k obtained here were almost the same as that in Fig. 15(a). The HI curves of $z=0.1$ and 0.2 showed a similar trend before region IV; however, the former persisted in increasing beyond U_k possibly owing to the interference of gas jetting near the gas distributor. At higher position ($z=0.4$ m), as shown in Fig. 16(b), the change of HI in regions I & II was not obvious between 0.45 and 0.5. It represented that no bubble growth happened here and the bubble coalescence and split reached to a dynamic equilibrium. As increasing U_o into region III, the HI increased sharply to comparative larger values than that in Fig. 16(a). It was because the breakage of large bubbles and agitation of solid particles were rather vigorous, thus caused higher degree of homogeneity near the bed surface. Nevertheless,

the U_c and U_k determined in Figs. 15(a), 16(a) and (b) were almost the same.

For glass beads and sand particles at lower position, as shown in Figs. 16(c) and (e), U_{ms} , U_c and U_k were clearly determined. At the axial position near the top of bed ($z=0.4$ m), no U_{ms} were characterized because large bubbles/slugs grew fast to stable maximum size subjected to the bed diameter at relatively lower gas velocity. So HI did not vary apparently in regions I & II, as shown in Figs. 16(d) and (f). Furthermore, the transition from regions III to IV was rather early at higher axial position. That was because the bottom dense bed height decreased with increasing superficial gas velocity, thus the pressure probe was exposed to the dilute phase/splash zone earlier for higher position. This result coincided with that obtained by the statistic analysis in Section 4.1.1.

4.2.5. Effect of static bed height on HI

Figs. 17 and 18 show the HI at $z=0.1$ and 0.4 m, respectively, with different static bed heights for sand particle in CFB-B system. Evidently the higher the static bed height was, the lower the HI values was obtained. The reason corresponding to this result was that the higher H_s might produce more stable

Fig. 19. Comparison of the Re_c and Re_k determined by standard deviation of APF and HI with predicted values calculated from Eqs. (13) and (14).

and larger bubbles in the beds, therefore, less change and lower values of HI were found. Additionally, the U_c determined from HI for $H_s = 0.4$ and 0.5 m were almost the same (Figs. 17(b) and (c) and 18(b) and (c)); however, it was quite different for $H_s = 0.6$ m (Figs. 17(a) and 18(a)). Significant slugging flow was observed for sand particles of $H_s = 0.6$ m and the breakup of large bubbles/slugs would be delayed, as discussed in Section 4.1.2. Hence, the U_c of $H_s = 0.6$ m, beyond which an obvious increase of HI was observed, was higher than those of $H_s = 0.4$ and 0.5 m. The U_k in these diagrams seemed to be independent of H_s and was somewhat lower/higher than the blow out velocity U_{se} as mentioned above. This fact could imply that the slugging flow for the sand particles still existed in the turbulent flow regime and the big bubbles/slugs kept breaking down until the fast fluidization flow regime was approached.

Based on Figs. 15 and 16, the transition velocities U_c and U_k were successfully determined by the HI curve even at the lower axial position of dense bed where no remarkable U_k was detected by the classical standard deviation curve. Shou and

Leu (2005a) also proposed another method to identify U_c and U_k of FCC particles by wavelet energy in PSDF of absolute pressure fluctuation signals. At the same time, they successfully identified U_c and U_k of sand particles by the standard deviation of wavelet reconstructed pressure signals (Shou and Leu, 2005b). Therefore, it can be concluded that wavelet analysis is indeed an effective tool for analyzing the pressure fluctuations and identifying the transition velocities between different flow regimes in fluidized beds.

Fig. 19 shows the comparison of U_c and U_k , obtained from standard deviation curves (in Figs. 3 and 5) and HI curves (in Figs. 15 and 16), with the predicted values calculated by Eqs. (13) and (14). In Fig. 19(a), the transition velocity U_c determined by the standard deviation of APF and HI curve coincided well with each other. However, they were somewhat smaller than the predicted values owing to the relatively lower H_s used in this study. Besides, the transition velocity U_k of sand particle obtained from HI curves was higher than that of standard deviation curves and predicted value, as shown in Fig. 19(b). This result was attributed to that gas voids in dense phase continued to collapse with increasing gas velocity even over the turbulent flow regime where the level-off of standard deviation appeared. Thus, HI persisted in increasing till the breakdown of gas void stops. To confirm whether the results were dependent on the properties of particles, further studies should be explored.

5. Conclusions

Transition velocities of FCC (Geldard A group), glass beads and sand particles (Geldard B group) from the bubbling/slugging to the turbulent flow regimes in circulating fluidized bed systems had been characterized by using statistical and wavelet multi-resolution analysis on the absolute pressure fluctuations acquired from different axial positions and static bed heights.

Based on statistical analysis, the transition velocity U_c was independent of the axial position of pressure probes, however, U_k decreased along the axial position due to the relationship between the change of the standard deviation of APF and the corresponding solid hold-up in the axial direction. Besides, increasing static bed height caused both U_c and U_k to increase. U_k could not be clearly identified at the bottom of the dense bed ($z/H_s < 0.5$) or the above splash zone ($z/H_s > 1$) and was ambiguous for the deeper bed of sand particles ($H_s = 0.6$ m). An appropriate interval of the relative bed depth (z/H_s) from 0.5 to 1.0 was recommended for identification of U_c and U_k by the APF measurement. U_c and U_k obtained in the specific interval of z/H_s fitted with Eqs. (13) and (14) are deduced from the data in this study and the literatures.

From wavelet analysis, the multi-scale behaviors of APF in circulating fluidized beds had been extracted by means of multi-resolution analysis (MRA). It provided a deep insight of the absolute pressure fluctuation signals and more information that the conventional statistic analysis was unable to do. A redefined variable, homogeneous index HI, obtained from the energy ratio of the SF and LF subsignals, contributed an alternative way on determining the transition velocities and characterizing the

flow regimes. It not only marked the transition velocity U_{ms} , U_c and U_k , but also discriminated the bubble growth dynamics of different kinds of particles in different flow regimes.

Notation

$A_J(t)$	approximation signal of level J , N/m^2
Ar	Archimedes number, dimensionless
APF	absolute pressure fluctuation, N/m^2
$d_{j,k}$	detail coefficient of level j , dimensionless
d_p	mean particle size, μm
$D_j(t)$	detail signal of level j , N/m^2
D_t	bed diameter, m
DC	DC trend of original signal, N/m^2
DPF	differential pressure fluctuations, N/m^2
E	energy of original signal, $(N/m^2)^2$
E_J^A	energy fraction of approximation signal of level J , $(N/m^2)^2$
E_J^D	energy fraction of detail signal of level J , $(N/m^2)^2$
H_d	bottom dense bed height, m
H_s	static bed height, m
HI	homogeneous index, dimensionless
I	integer, dimensionless
LF	large-pressure-fluctuation subsignal, N/m^2
N	number of data points, dimensionless
PF	pressure fluctuations, N/m^2
PSDF	power spectral density function, $(N/m^2)^2 s$
R^2	square of correlation coefficient, dimensionless
Re_c	Reynolds number based on U_c , dimensionless
Re_k	Reynolds number based on U_k , dimensionless
$s_{j,k}$	approximation smooth coefficient, dimensionless
s.d.	standard deviation of APF, N/m^2
SF	small-pressure-fluctuation subsignal, N/m^2
t	time, s
U_c	transition velocity at which the standard deviation of PF reaches a maximum, m/s
U_k	superficial gas velocity corresponding to the leveling-off standard deviation of pressure fluctuations as U_o increases, m/s
U_{mf}	minimum fluidization gas velocity, m/s
U_{ms}	minimum slugging gas velocity, m/s
U_o	superficial gas velocity in the riser, m/s
U_{se}	onset velocity of significant solids entrainment, m/s
U_t	terminal velocity, m/s
U_{tr}	transport velocity, m/s
$\bar{x}$	mean of $x(t)$, N/m^2
$x(t)$	time series of pressure fluctuation signal, N/m^2
z	axial position of pressure probe above the distributor, m

Greek letters

ε_s	solid hold-up, dimensionless
ρ_p	particle density, kg/m^3

σ_x	standard deviation of time series signal $x(t)$, N/m^2
ϕ	father wavelet, dimensionless
$\phi_{j,k}$	dilated father wavelet, dimensionless
ψ	mother wavelet, dimensionless
$\psi_{j,k}$	dilated mother wavelet, dimensionless

Subscripts

j	level of MRA
J	the maximum level of MRA
k	time shift
m	the specific level in this work

References

- Bai, D., Shibuya, E., Nakagawa, N., Kato, K., 1996. Characterization of gas fluidization regimes using pressure fluctuations. *Powder Technology* 87, 105–111.
- Bi, H.T., Fan, L.S., 1992. Existence of turbulent regime in gas–solid fluidization. *A.I.Ch.E. Journal* 38 (2), 297–301.
- Bi, H.T., Grace, J.R., 1995. Effect of measurement method on velocities used to demarcate the transition to turbulent fluidization. *Chemical Engineering Journal* 57, 261–271.
- Bi, H.T., Grace, J.R., Zhu, J.X., 1995. Regime transitions affecting gas–solids suspensions and fluidized beds. *Transactions IChemE, Part A, Chemical Engineering Research and Design* 73, 154–161.
- Bi, H.T., Ellis, N., Abba, I.A., Grace, J.R., 2000. A state-of-the-art review of gas–solid turbulent fluidization. *Chemical Engineering Science* 55, 4789–4825.
- Brereton, C.M.H., Grace, J.R., 1992. The transition to turbulent fluidization. *Transactions IChemE, Part A, Chemical Engineering Research and Design* 70, 246–251.
- Bruce, A., Gao, H.Y., 1996. *Applied Wavelet Analysis with S-PLUS*. Springer, New York, pp. 11–39.
- Cai, P., Chen, S.P., Jin, Z.Q., Wang, Z.W., 1989. Effect of operating temperature and pressure on the transition from bubbling to turbulent fluidization. *A.I.Ch.E. Symposium Series* 85 (270), 37–43.
- Cai, P., Jin, Y., Yu, Z.Q., Wang, Z.W., 1990. Mechanism of flow regime transition from bubbling to turbulent fluidization. *A.I.Ch.E. Journal* 36, 955–956.
- Chehbouni, A., Chaouki, J., Guy, C., Klvana, D., 1994. Characterization of the flow transition between bubbling and turbulent fluidization. *Industrial & Engineering Chemistry Research* 33, 1889–1896.
- Chen, A.H., Bi, H.T., 2003. Pressure fluctuations and transition from bubbling to turbulent fluidization. *Powder Technology* 133, 237–246.
- Cui, H., Mostoufi, N., Chaouki, J., 2000. Characterization of dynamic gas–solid distribution in fluidized beds. *Chemical Engineering Journal* 79, 134–143.
- Dhodapkar, S.V., Klinzing, G.E., 1993. Pressure fluctuation analysis for a fluidized bed. *A.I.Ch.E. Symposium Series* 89 (296), 170–183.
- Ellis, N., Briens, L.A., Grace, J.R., Bi, H.T., Lim, C.J., 2003. Characterization of dynamic behaviour in gas–solid turbulent fluidized bed using chaos and wavelet analyses. *Chemical Engineering Journal* 96, 105–116.
- Ellis, N., Bi, H.T., Lim, C.J., Grace, J.R., 2004. Hydrodynamics of turbulent fluidized beds of different diameters. *Powder Technology* 141, 124–136.
- Grace, J.R., Bi, H.T., 1997. Introduction to circulating fluidized beds. In: Grace, J.R., Avidan, A.A., Knowlton, T.M. (Eds.), *Circulating Fluidized Beds*. Blackie Academic & Professional, New York, p. 8.
- Grace, J.R., Sun, G., 1991. Influence of particle size distribution on the performance of fluidized bed reactors. *The Canadian Journal of Chemical Engineering* 69, 1126–1134.
- Haider, A., Levenspiel, O., 1989. Drag coefficient and terminal velocity of spherical and nonspherical particles. *Powder Technology* 58, 63–70.
- Horio, M., 1986. High velocity operation of fluidized beds. *Journal Powder Technology Japan* 23, 80–90.

- Horio, M., Ishill, H., Nishimuro, M., 1992. On the nature of turbulent and fast fluidized beds. *Powder Technology* 70, 239–246.
- Jin, Y., Yu, Z.Q., Wang, Z., Cai, P., 1986. A criterion for transition from bubbling to turbulent fluidization. In: Østergaard, K., Sørensen, A. (Eds.), *Fluidization*, vol. V. Engineering Foundation, New York, pp. 289–296.
- Johnsson, F., Zjiverveld, R.C., van den bleek, C.M., Leckner, B., 2000. Characterization of fluidization regimes by time-series analysis of pressure fluctuations. *International Journal of Multiphase Flow* 26, 663–715.
- Judd, M.R., Goosen, R., 1989. Effects of particle shape on fluidization characteristics of fine particles in the freely bubbling and turbulent regimes. In: Grace, J.R., Shemilt, L.W., Bergougnou, M.A. (Eds.), *Fluidization*, vol. VI. Engineering Foundation, New York, pp. 41–48.
- Kashkin, V.N., Lakhmostov, V.S., Zolotarskii, I.A., Noskov, A.S., Zhou, J.J., 2003. Studies on the onset velocity of turbulent fluidization for alpha-alumina particles. *Chemical Engineering Journal* 91, 215–218.
- Lee, G.S., Kim, S.D., 1988. Pressure fluctuations in turbulent fluidized beds. *Journal of Chemical Engineering of Japan* 21, 515–521.
- Leu, L.P., Huang, J.W., Gua, B.B., 1990. Axial pressure distribution in turbulent fluidized beds. In: Lu, W.M., Leu, L.P. (Eds.), *Proceedings of Asian Conference on Fluidized-Bed and Three-Phase Reactor*. Kenting, Taiwan, pp. 71–79.
- Lu, X., Li, H., 1999. Wavelet analysis of pressure fluctuation signals in a bubbling fluidized bed. *Chemical Engineering Journal* 75, 113–119.
- Makkawi, Y.T., Wrighti, P.C., 2002. Fluidization regimes in a conventional fluidized bed characterized by means of electrical capacitance tomography. *Chemical Engineering Science* 57, 2411–2437.
- Mori, S., Hashimoto, O., Haruta, T., Mochizuki, K., Matsutani, W., Hiraoka, S., Yamada, I., Kojima, T., Tuji, K., 1988. Turbulent fluidization phenomena. In: Basu, P., Large, J.F. (Eds.), *Circulating Fluidized Beds Technology*, vol. II. Pergamon Press, Oxford, pp. 105–112.
- Mori, S., Liu, D., Kato, K., Kobayashi, E., 1992. Flow regimes and critical velocity in a circulating fluidized bed. *Powder Technology* 70, 223–227.
- Park, S.H., Kang, Y., Kim, S.D., 2001. Wavelet transform analysis of pressure fluctuation signals in a pressurized bubbling column. *Chemical Engineering Science* 56, 6259–6265.
- Perales, J.F., Coll, T., Llop, M.F., Puigjaner, L., Arnaldos, J., Casal, J., 1991. On the transition from bubbling to fast fluidization regimes. In: Basu, P., Horio, M., Hasatani, M. (Eds.), *Circulating Fluidized Beds Technology*, vol. III. Pergamon Press, Oxford, pp. 73–78.
- Ren, J., Li, J., 1998. Wavelet analysis of dynamic behavior in fluidized beds. In: Fan, L.S., Knowlton, T.M. (Eds.), *Fluidization*, vol. IX. Engineering Foundation, Colorado, pp. 629–636.
- Rhodes, M.J., 1996. What is turbulent fluidization? *Powder Technology* 88, 3–14.
- Rhodes, M.J., Geldart, D., 1986. Transition to turbulence. In: Østergaard, K., Sørensen, A. (Eds.), *Fluidization*, vol. V. Engineering Foundation, New York, pp. 281–288.
- Satija, S., Fan, L.S., 1985. Characteristics of slugging regime and transition to turbulent regime for fluidized beds of large coarse particles. *A.I.Ch.E. Journal* 31 (9), 1554–1562.
- Shou, M.C., Leu, L.P., 2005a. Energy of power spectral density function and wavelet analysis of absolute pressure fluctuation measurements in fluidized beds. *Trans IChemE, Part A, Chemical Engineering Research and Design* 83 (A5), 478–491.
- Shou, M.C., Leu, L.P., 2005b. Identification of transition velocities in fluidized beds using wavelet analysis. *Journal of Chemical Engineering of Japan* 38 (6), 409–421.
- Son, J.E., Choi, J.H., Lee, C.K., 1988. Hydrodynamics in a large circulation fluidized bed. In: Basu, P., Large, J.F. (Eds.), *Circulating Fluidized Beds Technology*, vol. II. Pergamon Press, Oxford, pp. 113–120.
- Sun, G.L., Chen, G., 1989. Transition to turbulent fluidization and its prediction. In: Grace, J.R., Shemilt, L.W., Bergougnou, M.A. (Eds.), *Fluidization*, vol. VI. Engineering Foundation, New York, pp. 33–44.
- Tsukada, M., Nakanishi, D., Horio, M., 1993. The effect of pressure on the phase transition from bubbling to turbulent fluidization. *International Journal of Multiphase Flow* 19, 27–34.
- Wen, C.H., Yu, Y.H., 1966. A generalized method for predicting the minimum fluidization velocity. *A.I.Ch.E. Journal* 12, 610–612.
- Yerushalmi, J., Cankurt, N.T., 1979. Further studies of the regimes of fluidization. *Powder Technology* 24, 187–205.
- Yerushalmi, J., Cankurt, N.T., Geldart, D., Liss, B., 1978. Flow regimes in vertical gas–solid contact systems. *A.I.Ch.E. Symposium Series* 174 (176), 1–12.
- Zhao, X., Yang, G.L., 1991. Critical turbulent velocity for fluidized beds with baffles. In: Kwauk, M., Hasatani, M. (Eds.), *Proceedings of the Fourth China–Japan Fluidization Conference*. Science Press, Beijing, pp. 196–201.
- Zjiverveld, R.C., Johnsson, F., Marzocchella, A., Schouten, J.C., van den Bleek, C.M., 1998. Fluidization regimes and transitions from fixed bed to dilute transport flow. *Powder Technology* 95, 185–204.