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Wavelet analysis of pressure fluctuation signals in a bubbling fluidized bed

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Abstract

Pressure fluctuations of fluidized beds have been used to evaluate the fluidization quality. In bubbling fluidized beds, the bed behavior is characterized by bubbling. The information indicated by the pressure fluctuation signals can be applied to describe those behaviors. The signals representing the characteristics of bubbling can be separated from original signals through discrete Wavelet analysis. Considering the principles of Wavelet, the Scale 4 detail signals can reveal the bubble behaviors in a fluidized bed. The peak frequency of the Scale 4 detail signal stands for the bubbling frequency and the peak amplitude for the bubble size.

Keywords: Fluidization; Wavelet analysis; Bubbling frequency; Bubble size

1. Introduction

It has been demonstrated that the pressure fluctuations in a bubbling fluidized bed are caused by the motion of bubbles [1,2], and the amplitude of the pressure fluctuations is related to the bed density and the size of bubble [2]. Recently, it has been shown that the pressure fluctuation measured is a result of slow and fast propagating pressure waves that move upwards and downwards [3]. Upward moving compression waves originate from the formation and coalesce of gas bubbles, and downward moving compression waves are caused by gas bubble eruptions at the fluidized bed surface [3]. He et al. [4] demonstrated that the pressure fluctuations in a gas–solid fluidized bed could be partitioned into a fractional Brownian motion (FBM) and Gaussian white noise (GWN). The GWN part of the pressure-fluctuation signal is caused by the jet and the formation of the small bubbles near the distributor [4]. The pressure fluctuations caused by such origins are transmitted upward and reduced gradually with the increase of the bed height. The GWN is superimposed on the largest pressure fluctuation that can be represented by FBM [4].

In summary, pressure fluctuations in a fluidized bed can reflect the bubble behavior features, such as the bubbling frequency and bubble size. Although, many models have been developed to describe these behaviors [1,5–8], a valid method to process the pressure fluctuation signals is still not found.

In this paper, the results state that Wavelet analysis can be used to analyze the pressure fluctuation signals effectively.

2. Discrete Wavelet transform

The wavelet transform of a signal $f(x)$ is defined as

$$W_s f(x) = \int_{-\infty}^{+\infty} f(u)\psi_s(x-u)\mathrm{d}u \tag{1}$$

where

$$\psi_s(x) = \frac{1}{s}\psi\left(\frac{x}{s}\right) \tag{2}$$

$\psi(x)$ is a basic wavelet function. In fact, the wavelet function replaces $e^{-ix\omega}$ in the Fourier transform. Wavelet transform overcomes some shortcomings of Fourier transform. For example, Wavelet transform can provide information of a random signal with time and space, but Fourier transform can not. For practical implementation, the discrete wavelet transform is used. The following discrete wave filter functions are constructed corresponding to $\psi(x)$

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$$H(\omega) = \sum_{n=-\infty}^{+\infty} h_n e^{-in\omega} \quad (3)$$

$$G(\omega) = \sum_{n=-\infty}^{+\infty} g_n e^{-in\omega} \quad (4)$$

refer to [9–11] for details

According to Wavelet transform, the original signals can be resolved into multi-resolution signals with different frequency bands. It is shown that the raw data can be decomposed into different scale signals and detail signals (wavelet transform), and the original signal may be reconstructed from the information contained in the last scale signal and detail signals [12]. Ren and Li [13] indicated that with increasing resolution, the amplitude of the resolved signals decreases for the pulse change (noise), increases for the gradual change and keeps constant for step variation of resolution-independent.

A random signal is employed to elucidate the process of wavelet transform) (see Fig. 1). First, the original signal (Fig. 1(a)) is resolved into Scale 1 signal and Scale 1 detail signal. Scale 1 detail signal, i.e., the wavelet transform, captures the information with high frequency. The Scale 1 signals, i.e., the remainder of the original signals through wavelet filter, can be further decomposed into Scale 2 signals and Scale 2 detail signals. Through a family of

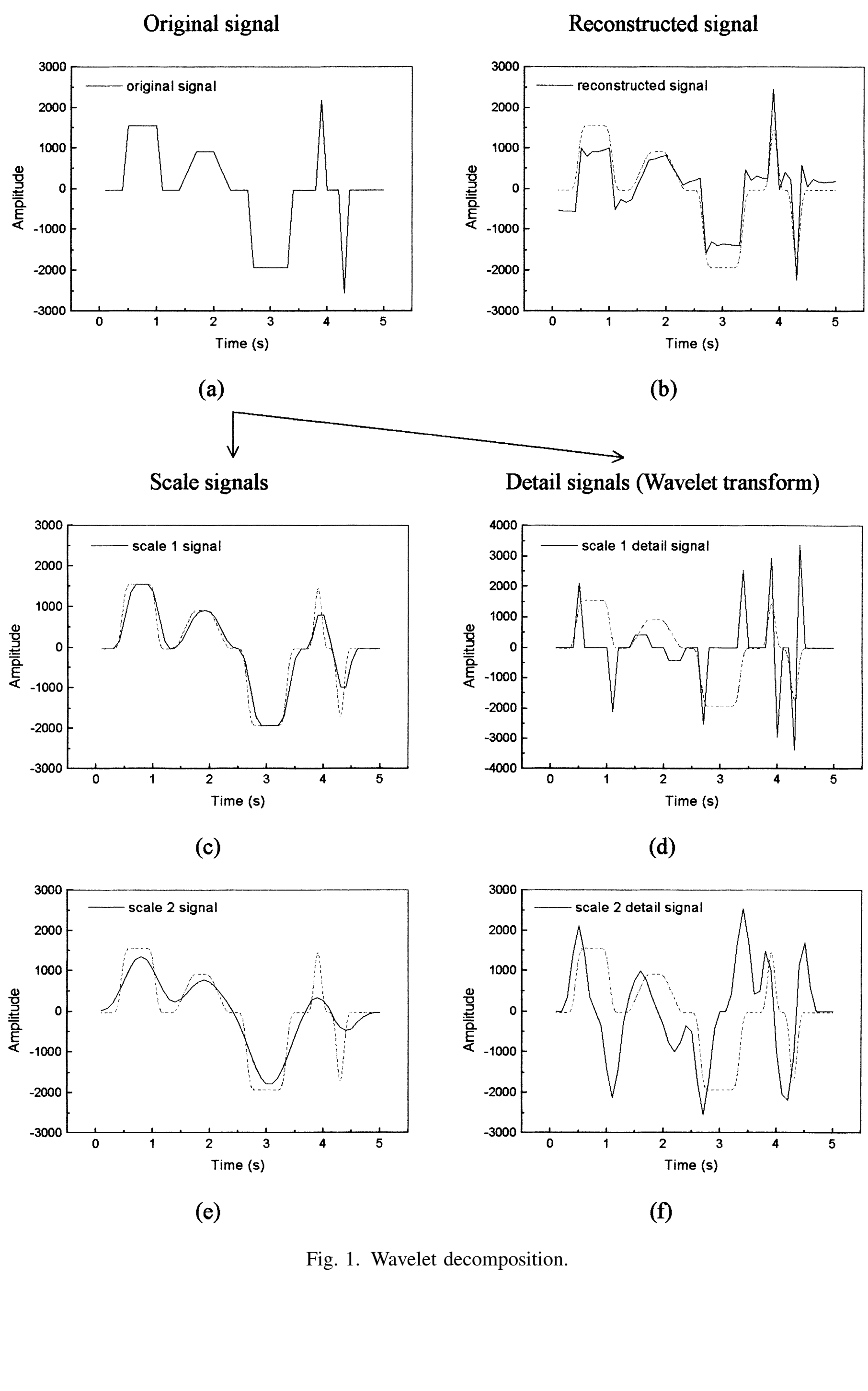


Fig. 1. Wavelet decomposition.

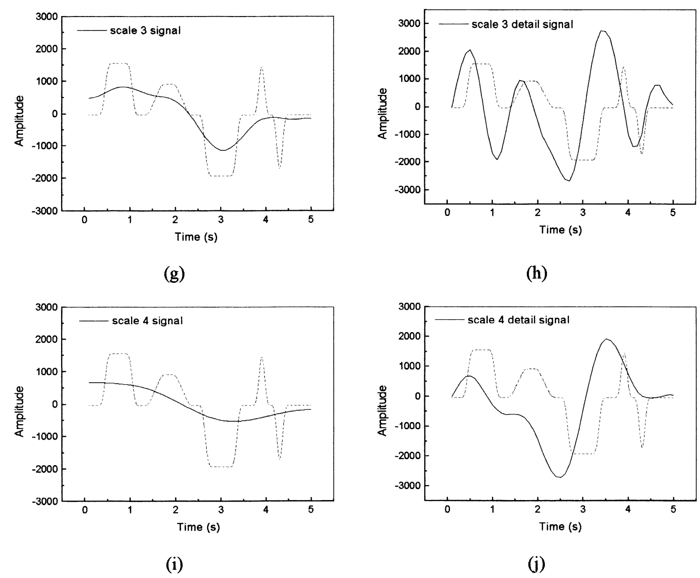


Fig. 1. (*Continued*).

Wavelet filter, a series of detail signals is obtained with different frequency band (see Fig. 1(d), Fig. 1(f), Fig. 1(h), Fig. 1(j)). Scale 4 signal is the remainder signal by wavelet transform. The original signal can be reconstructed from the Scale 4 signal and other detail signals (see Fig. 1(b)). The variations of three kinds of changes (pulse, gradual change and step variation) are shown in Fig. 1(d), Fig. 1(f), Fig. 1(h), and Fig. 1(j). They are in agreement with those in ref. [13].

In a bubbling fluidized bed, the pressure fluctuation is associated with the bubble motion. Through wavelet filter, the pressure fluctuation signals are resolved into multi-resolution signals, such as the three kinds of changes mentioned above. They are mainly originated from various bubble behaviors. For further study on pressure fluctuations of a gas–solid fluidized bed, the following experiments are carried out.

3. Experimental

The experiments were carried out in a glass column of 35 mm OD, 33 mm ID, 600 mm in height (see Fig. 2). A sintered porous plate was used as the gas distributor. The pressure probe was vertically installed against the wall of the bed column. The distance between the probe and the distributor was 15 mm. The pressure transducer was connected with DATA MODEL 611/1 to pick pressure data. A compressor provided the compressed air. The sampling frequency was 1000 Hz, and 7000 points were collected each time.

The method used for computing the one-dimensional orthonormal wavelet transform of a signal is the Mallat's pyramidal algorithm.

The properties of particles used are listed in Table 1.

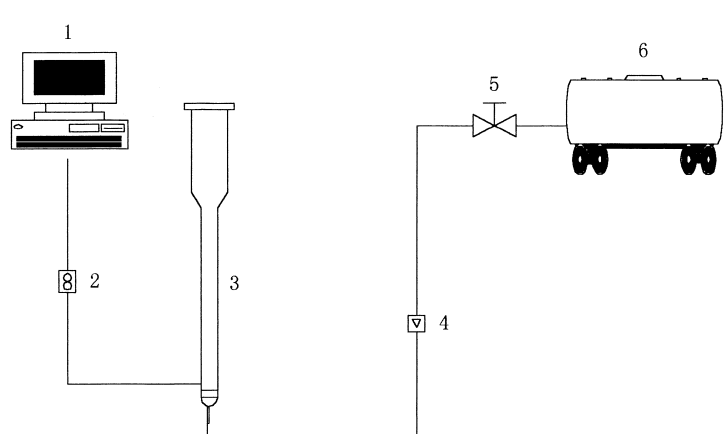


Fig. 2. Schematic diagram of experimental set-up 1: DATA MODEL 611/1; 2: pressure transducer; 3: bubbling fluidized bed; 4 rotameter; 5 valve; 6 compressor.

Table 1
Properties of particles

Material	Diameter (mm)	Density (kg m^{-3})
FCC	0.076	929.5

4. Results and discussion

4.1. Wavelet analysis of pressure fluctuation signals

In a gas–solid fluidized bed, the pressure fluctuations measured are a result of propagating waves.

Schaaf et al. [3] suggested that the upward propagation of the pressure fluctuation wave of a gas pulse could be divided into three phases, as shown in Fig. 3. The first phase is a homogenous oscillation representing bubble formation, the second represents a bubble rising along the fluidized bed, and the third represents a bubble eruption on the bed surface. During the whole process, the first phase provides the maximum pressure fluctuation. When the pressure wave propagates downward, the pressure amplitude does not attenuate below the injection point and is linearly dependent on $h_{\mathrm{bed}}-h_{\mathrm{probe}}$ above the injection point [3]. In a freely bubbling fluidized bed, the pressure fluctuations can be regarded as the mixture of pressure waves traveling upward and downward [3]. Thus, it can be seen that the large fluctuations originate from the bubble formation.

Thus, we can gain the information concerning of the pressure variation degree conveniently by using Wavelet analysis. Fig. 4(a) shows that raw pressure data and their decomposed signals.

The pressure fluctuation signal in a bubbling fluidized bed is resolved into four resolution detail signals from Scale 1 $(W_2^1 f(x))$ to Scale 4 $((W_2^4 f(x))$ with different frequency bands. That is, original signals are decomposed by order on the basis of frequency. The first resolved component is one with high frequency, such as Scale 1 $(W_2^1 f(x))$ detail signals (see Fig. 4(b)). Successively, detail signals with different frequencies are separated one by one (from Fig. 4(c) to Fig. 4(j) Fig. 5). According to Ren's method, with increasing resolution, the amplitude of the resolved detail signals decreases for the pulse change (noise), increases for the gradual change, and keeps constant for step variation of resolution-independent [13]. Then, the different resolution detail signals reflect the varying degrees and speeds in point of time with different frequency bands. In this work, the pressure fluctuation signals caused by slight bed disturbance or noise are filtered step by step in resolution. The detail wavelet Scale 4 signals represent the bulk of radical pressure fluctuations in a bubbling fluidized bed, in which, only the bubbles can bring about these high pressure fluctuations. As a result, every peak of Scale 4 detail signals stands for a bubble. So, we generated here two questions. (1) Does the amplitude of those peaks represent the bubble size? (2) Does the frequency of those peaks represent the bubble frequency?

In order to answer these questions, the bubble frequency and size from wavelet analysis are compared with those of Darton's model [5].

4.2. Define of the minimum fluidization velocity and signal peaks

In this experiment, U_{mf} of FCC particles is defined by the following equation [14]:

$$\frac{d_{\mathrm{p}} U_{\mathrm{mf}} \rho_{\mathrm{s}}}{\mu} = \left[(33.7)^2 + 0.0408 \frac{d_{\mathrm{p}}^3 \rho_{\mathrm{g}} \left(\rho_{\mathrm{s}} - \rho_{\mathrm{g}} \right) g}{\mu^2} \right]^{1/2} - 33.7 \quad (5)$$

For fine particles, the Eq. (5) can be revised into

$$U_{\mathrm{mf}} = \frac{d_{\mathrm{p}}^2 \left(\rho_{\mathrm{s}} - \rho_{\mathrm{g}} \right) g}{1650\,\mu} \quad (6)$$

According to the above two equations, U_{mf} of FCC particles used in the experiment is 0.00179 m s^{-1}.

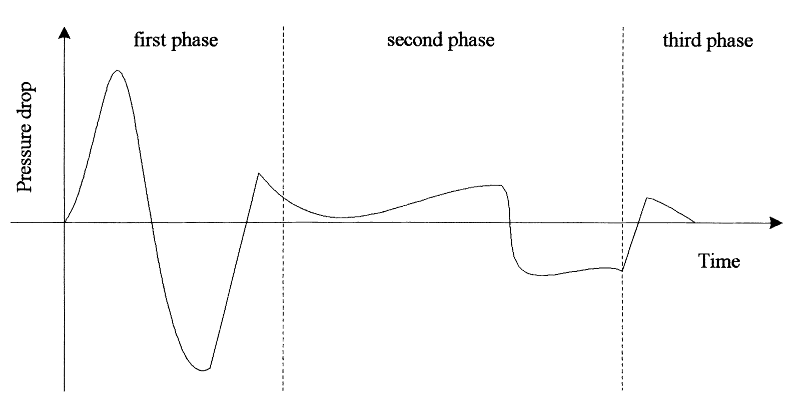


Fig. 3. Schematic of the bed respond to a gas pulse.

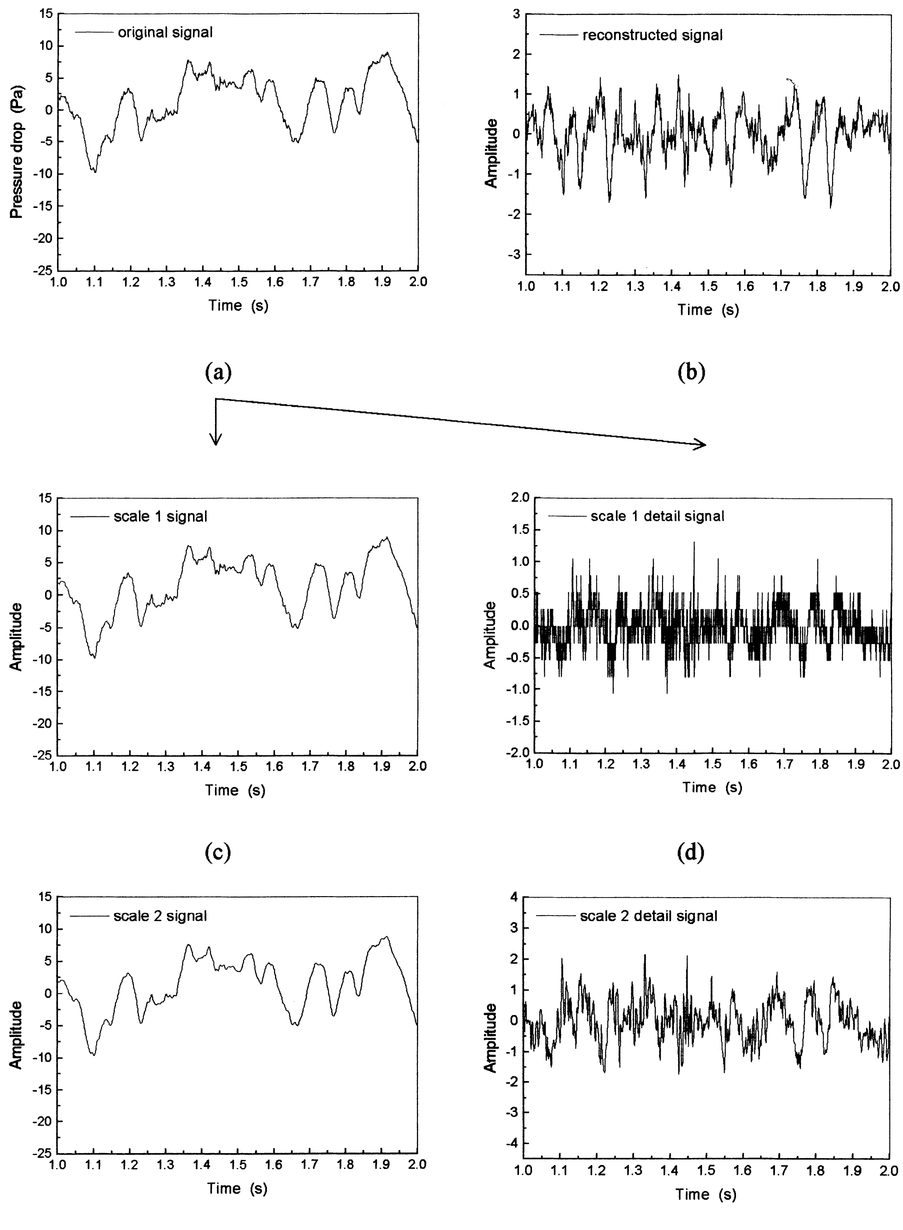


Fig. 4. Multi-resolution of pressure fluctuation signals ($U = 0.146$ m s^{-1}) (a) original signal; (b) reconstructed signal; (c) Scale 1($W_2^1 f(x)$) signal; (d) Scale 1($W_2^1 f(x)$) detail signal; (e) Scale 2 ($W_2^2 f(x)$) signal; (f) Scale 2 ($W_2^2 f(x)$) detail signal; (g) Scale 3 ($W_2^3 f(x)$) signal; (h) Scale 3 ($W_2^3 f(x)$) detail signal; (i) Scale 4 ($W_2^4 f(x)$) signal; (j) Scale 4 ($W_2^4 f(x)$) detail signal.

The peak points are chosen with the aid of Microcal Origin 5.0 software. The width, height and minimum height of pick-peaks toolbar are 0.50, 9.00 and 5.00, respectively. The average peak frequency is obtained from the following equation.

$$f = \frac{N}{t} \tag{7}$$

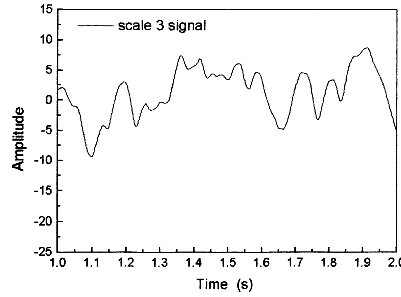
The average amplitude of peaks is described as

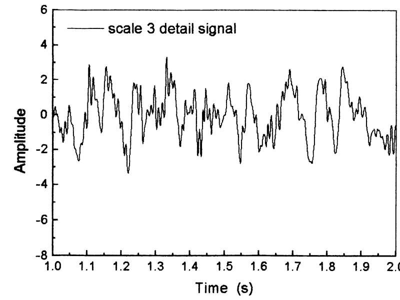
$$A_{s4} = \frac{\sum A}{N} \tag{8}$$

4.3. The bubble frequency related to the peak frequency of Scale 4 detail wavelet signals

Many researchers pointed out that the excess gas (U–U_{mf}) could cause the bubbles [7–8], so the bubbling frequency is a function of U–U_{mf}.

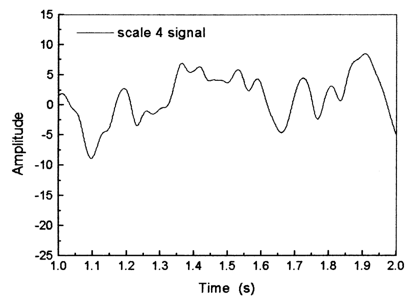
In order to clarify that the peak frequency of Scale 4 detail signals is the bubbling frequency, Darton's model is examined and compared. Darton et al. [5] indicated that the bubbling frequencies fell with U–U_{mf}. The relationship of the bubble frequency and (U–U_{mf}) is





(g)

(h)



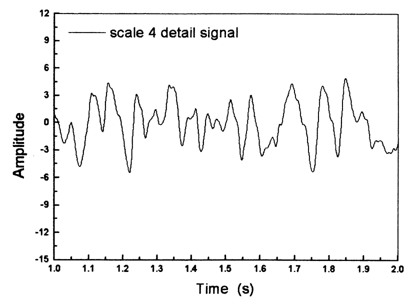


Fig. 4. (*Continued*).

given as

$$f_b = 12.1\, g^{0.6}(U - U_{mf})^{-0.2}\left(h + 4.0\sqrt{A_0}\right)^{-2.4} \quad (9)$$

It is obvious that f_b is directly proportional to $(U - U_{mf})^{-0.2}$. Fig. 6 shows the relationship between peak frequency and $(U - U_{mf})^{-0.2}$ according to the experimental data. It can be seen from Fig. 6 that the fitted line passes through the zero point, and the following relationship exists:

$$f \sim (U - U_{mf})^{-0.2}$$

This agrees well with Darton's model of $f_b \sim (U - U_{mf})^{-0.2}$. Therefore,

$$f \sim f_b$$

It proves that the peak frequency of Scale 4 signal can represent the bubbling frequency.

4.4. The bubble size related to the average peak value of Scale 4 detail wavelet signals

According to Darton's model,

$$D_e = \frac{0.54\,(U - U_{mf})^{0.4}\left(h + 4.0\sqrt{A_0}\right)^{0.8}}{g^{0.2}} \quad (10)$$

the bubble size is proportional to $(U - U_{mf})^{0.4}$. According to the experimental data, the relationship between average

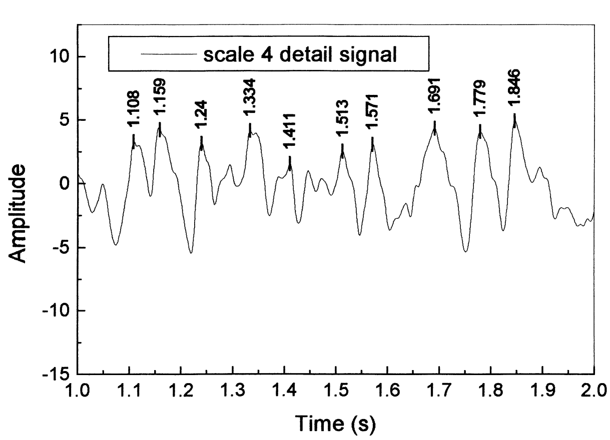


Fig. 5. Peaks of Scale 4 detail wavelet signal.

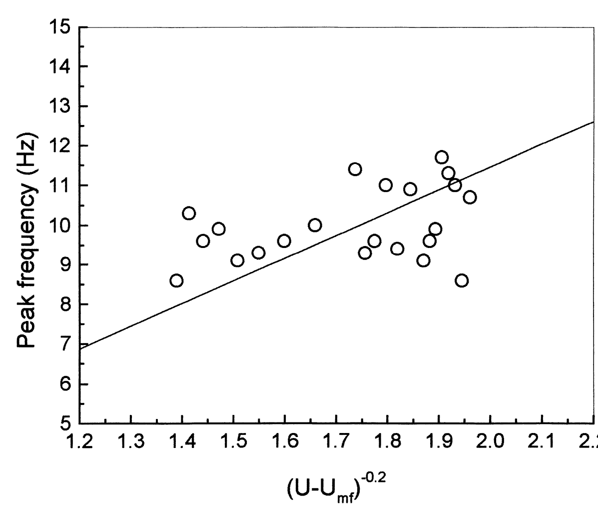


Fig. 6. Peak frequency versus $(U - U_{mf})^{-0.2}$.

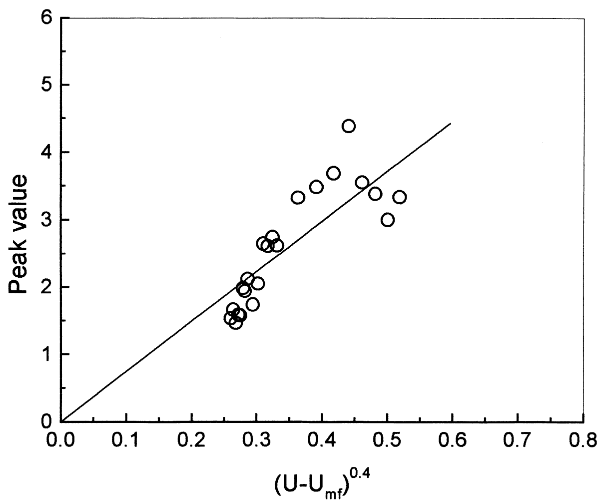


Fig. 7. Average peak value versus $(U–U_{mf})^{0.4}$.

peak value A_{s4} and $(U-U_{mf})^{0.4}$ is shown in Fig. 7. It can also be seen from Fig. 7 that the average peak value of the Scale 4 detail signal is proportional to $(U-U_{mf})^{0.4}$ as well. Thus, the following relationship exists:

$$A_{s4} \sim (U-U_{mf})^{0.4}$$

This agrees with Darton's model of $D_e \sim (U-U_{mf})^{0.4}$.

Therefore,

$$A_s \sim D_e$$

It states that the relative height of amplitude of peaks can represent the bubble size.

5. Conclusions

Wavelet analysis provides an effective tool for analyzing pressure fluctuation signals in a bubbling fluidized bed. Wavelet can filter pressure fluctuation signals and obtain the Scale 4 detail signals, which reflect the bubble behaviors. The peak frequency of these signals can represent the bubbling frequency, and the average peak value can represent the bubble size.

6. List of symbols

A	amplitude of a peak in Scale 4 signal
A_0	catchment area for a bubble stream at the distributor plate (m^2)
A_{s4}	average peak amplitude of Scale 4 signals
d_p	particle diameter (m)
D_e	equivalent spherical diameter of bubble (m)
f	average peak frequency (Hz)
f_b	bubbling frequency (Hz)
g	acceleration due to gravity (m s^{-2})
h	height in the bed (m)
h_{bed}	distance between bed surface and gas distributor (m)
h_{probe}	distance between probe and gas distributor (m)
N	number of peaks in the interval of time
t	interval of time (s)
U	gas velocity (m s^{-1})
U_{mf}	minimum fluidization velocity (m s^{-1})

6.1. Greek letters

μ	viscosity (Pas)
ρ_s	particle density (kg m^{-3})
ρ_g	gas density (kg m^{-3})

References

[1] J. Verloop, P.M. Heertjes, Periodic pressure fluctuations in beds, Chem. Eng. Sci. 29 (1974) 1035–1042.

[2] L.T. Fan, Tho-ching Ho, S. Hiraoka, W.P. Walawender, Pressure fluctuations in a fluidized bed, AIChE J. 27(3) (1981) 388–396.

[3] J. van der Schaaf, J.C. Schouten, C.M. van den Bleek, Origin propagation, origin propagation and attenuation of pressure waves in gas–solid fluidized beds, Powder Technol. 95 (1998) 220–233.

[4] Z. He, W. Zhang, K. He, B. Chen, Modeling pressure fluctuations via correlation structure in a gas–solids fluidized bed, AIChE J. 43(7) (1997) 1914–1920.

[5] R.C. Darton, R.D. LaNauze, J.F. Davidson, D. Harrison, Bubble growth due to coalescence in fluidized beds, Trans IChemE, 55 (1977) 274–280.

[6] A.P. Baskakov, V.G. Tuponogov, N.F. Filippovsky, A study of pressure fluctuations in a bubbling fluidized bed, Powder Technol. 45 (1986) 113–117.

[7] M. Carsky, M. Hartman, The bubble frequency in a fluidized bed at elevated pressure, Powder Technol. 61 (1990) 251–254.

[8] B.H. Nelson, C.L. Briens, M.A. Bergougnou, Pressure fluctuations at individual grid holes of a gas–solid fluidized bed, Powder Technol. 77 (1993) 95–102.

[9] S.G. Mallat, A theory for multiresolution signal decomposition: the wavelet representation, IEEE Trans. Pattern Anal. Machine Intelligence 117 (1989) 674–693.

[10] C.K. Cui, An introduction of Wavelets, Academic Press, 1992

[11] Qianqing Qin, Zongkai Yang, Practical Wavelet Analysis. Xi'an Xidian University Press, 1995, pp. 25–27 (in Chinese)

[12] B.R. Bakshi, H. Zhong, P. Jiang, L.-S. Fan, Analysis of flow in gas-liquid bubble columns using multi-resolution methods, Trans IChemE. 73 (Part A) (1995) 608–614.

[13] Jinqiang Ren, Jinghai Li, Wavelet analysis of dynamic behavior in fluidized beds, in: L.T. Fan, T.M. Knowlton (Eds.), Fluidization IX, 1998, pp. 629–636

[14] C.Y. Wen, Y.H. Yu, A generalized method for predicting the minimum fluidization velocity, AIChE J. 123 (1966) 610–612.