Nonintrusive Characterization of Fluidized Bed Hydrodynamics Using Vibration Signature Analysis

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There are many techniques to characterize the hydrodynamics of fluidized beds, but new techniques are still needed for more reliable measurement. Bed vibrations were measured by an accelerometer in a gas–solid fluidized bed to characterize the hydrodynamics of the fluidized bed in a nonintrusive manner. Measurements were carried out at different superficial gas velocities and particle sizes. Pressure fluctuations were measured simultaneously. Vibration signals were processed using statistical analysis. For the sake of the evaluation, the vibration technique was used to calculate minimum fluidization velocity. It was shown that minimum fluidization velocity can be determined from the variation of standard deviation, skewness, and kurtosis of vibration signals against superficial gas velocity of the bed. Kurtosis was proved to be a new method of analyzing vibration signals. Results indicate that analyzing the vibration signals can be an effective nonintrusive technique to characterize the hydrodynamics of fluidized beds. © 2009 American Institute of Chemical Engineers *AIChE J,* 56: 597–603, 2010
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Introduction

The gas–solid flow in a fluidized bed is characterized by very distinct flow structures. To understand these complicated flow structures, accurate and reliable techniques must be developed to determine hydrodynamic properties in the fluidized bed. Both intrusive and nonintrusive measurement techniques have been utilized to do this. Most investigators have used pressure signals and their fluctuations to determine formation, rise-up and eruption of bubbles,[1,2] velocity and size of bubbles,[3] and regime transition in the bed.[4,5] Optical fiber probe measurements and their fluctuations have also been extensively used for measuring the local velocity in fluidized beds and cluster identification.[6–8] These fluctuations can provide valuable information in fluidized beds such as cluster diameter and velocity.

Various methods have been used to analyze the dynamic changes of local phenomena in fluidization, such as statistical,[9,10] fractal, chaos, and wavelet analyses.[4,5] The standard deviation, coefficient of variation, kurtosis, and skewness are all statistical parameters that can be easily calculated, providing useful information about the hydrodynamics of the bed. The relationship between the amplitude of pressure signals and the excess gas velocity was modeled by Fan et al.[11] Pressure fluctuations were used by Puncochar et al.[12] to determine minimum fluidization velocity. They proposed that the standard deviation of the pressure fluctuation, σ_P, was related to the superficial velocity by the equation:

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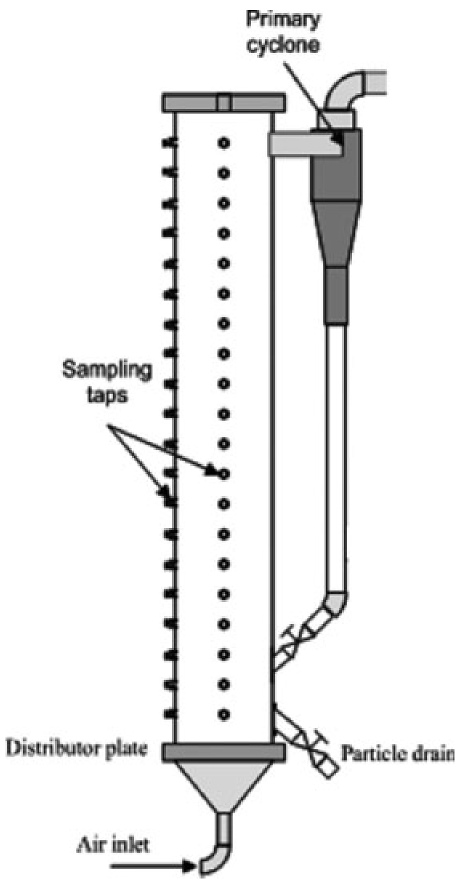

Figure 1. Schematic of the fluidized bed.

$$\sigma_P = C(U_G - U_{mf}) \quad (1)$$

According to Eq. 1, to get zero at $U_G = U_{m\sigma}$, Felipe and Rocha[13] verified the method of Puncochar et al.[12] in broader experimental conditions for fluidized beds of Geldart A and B powders. Davies and Fenton developed a model to express the particle size ratio of two batches of Geldart A material in terms of the standard deviation of the bed pressure drop.[14]

As mentioned earlier, pressure fluctuation and fiber optic measurements are common methods to determine hydrodynamic properties of fluidized beds. Yet in some cases, these methods are not reliable means of measurement. Because of their intrusiveness, these methods can alter the local hydrodynamics of the fluidized bed. Moreover, the local flow structure of the bed is extremely complex, making it hard to identify the origin of fluctuations amongst many simultaneously occurring phenomena. The best approach toward the understanding of such complex flow structure requires reliable data, which in turn depends on the measuring technique.

Nonintrusive techniques that measure bed vibration may represent a reliable measuring technique for the determination and characterization of the hydrodynamics of fluidized beds. Vibration signals could originate from the formation, movement, coalescence, break up, and eruption of bubbles within the bed. Another source of bed vibration is particle-wall collision. Particles that differ in size or density produce different vibration signals. Therefore, vibration signals in a fluidized bed directly reflect either the bubble characteristics or cluster characteristics. The main objective of this study was to introduce and test the applicability of vibration signals to characterize the hydrodynamics of fluidized beds. For the sake of comparison, pressure fluctuations were recorded simultaneously. Statistical analyses, namely standard deviation, skewness, and kurtosis, were used to analyze both the transient vibration data and pressure fluctuations taken in the dense fluidized bed.

Experiments

The experimental setup is shown in Figure 1. The experiments were carried out in a gas–solid fluidized bed made of a Plexiglas pipe of 15 cm inner diameter and 200 cm height. The whole system was electrically grounded to minimize electrostatic effects. Air at room temperature entered into the column through a perforated plate distributor of 435 holes with 7-mm triangle pitch and its flow rate was measured by a rotameter. Two cyclones, placed at the column exit, returned the entrained solids back to the bed. The static bed height in all experiments was set to 15 cm ($L/D = 1$). Sand particles with mean sizes of 150, 280, 490, and 720 μm and particle density of 2640 kg/m^3 were used. For obtaining granulometric distribution, the particles were sieved through a series of screens with standardized mesh size. The size distribution of the particles is listed in Table 1. The mean sizes reported in this table are harmonic mean size of particles.

Pressure fluctuation signals were collected at a sampling frequency of 400 Hz for 30 s. Two identical DJB accelerometers with sensitivity of 100 mV/ms^{-2} and with a cutoff frequency of 25 kHz were used to measure the vibration of the process equipment. The accelerometers were screwed onto the gluing studs located 5 and 10 cm above the distributor. Pressure fluctuations were recorded at the same conditions. To ensure the reproducibility of the sampled signals, the measurements were repeated three times at the same operating conditions.

The accelerometers produced analog signals that were conditioned and converted to digital using the B&K PULSE system with 3560 type hardware. It was found by analyzing

Table 1. Size Distribution of Sand Particles Used in This Work

	Weight Fraction			
d_{pi} (μm)	Sand I	Sand II	Sand III	Sand IV
1095	0	0	0	50
920.5	0	0	0	90
774	0	0	0	100
651	0	0	4	60
547.5	0	0	240	65
460	0	0	118	25
387	0	0	0	0
325.5	0	288	34	0
273.5	0	24	0	0
213.5	70	72	0	0
163	300	12	0	0
137	30	0	0	0
115	10	0	0	0
96.5	0	0	0	0
d_p (μm)	150	280	490	720

Table 2. Calculated Minimum Fluidization Velocity (m/s) from Different Methods

d_p (μm)	From Bed Pressure Drop	Wen and Yu (1966)	From σ		From S (Vibration)	From K (Vibration)
			Pressure Fluctuations	Vibration		
150	0.021	0.0198	0.0271	0.022	0.0221	0.0205
280	0.056	0.0616	0.0607	0.0613	0.0562	0.0587
490	0.17	0.186	0.121	0.162	0.191	0.185
720	0.41	0.0.397	–	0.407	0.4217	0.415

the frequency spectrum of the vibration signals that bed frequencies in this were limited to 8 kHz. Therefore, the sampling frequency was set to 25 kHz to prevent information loss associated with the vibration content of the signals. This frequency was determined using the Shanon-Nyquist criterion which states that the sampling frequency should be greater than the maximum frequency component within the frequency spectrum.[15]

To take into account oscillations caused by blower and bed oscillations and eliminate them from the vibration signals, the frequencies of these phenomena were measured in each experiment for the empty column. The frequencies of these external sources were identified and were then filtered out from the vibration signals using low pass and high pass filters.

Method of Analysis

Various methods have been applied to analyze time-series signals. These methods include time domain, frequency domain, and time-frequency analyses. Statistical measures that can be used to analyze the signals include standard deviation, skewness, and kurtosis. Puncochar et al.[12] and Felipe and Rocha[13] found that standard deviation of pressure measurement is appropriate to estimate U_{mf} of Geldart A and B particles. Lee and Kim used the skewness and kurtosis of pressure fluctuations to determine the transition from bubbling to turbulent regime.[16] They found that the maximum point in the kurtosis and the minimum point in the skewness correspond to transition velocities.

Analysis of frequency distribution has also been applied to time series data to identify the dominant frequency. Johnsson et al. showed that the shape of the power spectral density function (PSDF) of pressure fluctuation signals can be used to determine different modes of bubbles (single, multiple, and exploding bubbles).[17] For better resolution in the time-frequency domain, wavelet transform analysis has also been applied to nonlinear and transient time series data. Shou and Leu characterized different flow regimes of fluid cracking catalyst and sand in a circulating fluidized bed by the wavelet energy distribution of pressure fluctuation data.[5] They determined the transition velocities U_c and U_k by combining the PSDF and wavelet analysis of absolute pressure fluctuations. So far, bed vibration signals have not been used for determining the hydrodynamics of the fluidized bed. Statistical analysis of bed vibration was used in the present work for the identification of the hydrodynamics of the bed. Other techniques could also be applied to these signals for extracting different information about the quality of fluidization. Statistical parameters used in this study are explained in the following.

Standard deviation is a measure of the degree to which the data spreads around a mean value defined as follows:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{2}$$

where the mean value is evaluated from:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

Skewness, or the third central moment, is a measure of the lack of symmetry in the probability density function about the mean defined as:

$$S = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{(n-1)\sigma^3} \tag{4}$$

A distribution has positive skew if the right tail is longer and negative skew if the left tail is longer. This was also used to analyze both vibration and pressure fluctuation signals.

Kurtosis, or the 4th moment, is a measure of whether the data are peaked or flat relative to a normal distribution and is defined as:

$$K = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^4}{(n-1)\sigma^4} \tag{5}$$

Data sets with high kurtosis tend to have a distinct peak near the mean, decline rather rapidly and have heavy tails. Data sets with low kurtosis tend to have a flat top near the mean rather than a sharp peak.

Results and Discussion

Extensive sets of vibration and pressure signals were recorded by altering gas flow rate and particle size. Typical vibration and pressure signals, recorded by the accelerometer and pressure probe, are shown in Figures 2a, b, respectively. The fluctuations may represent bubble characteristics as well as particle-wall interactions. Obviously, it is impossible to extract reliable information from such raw signals. Therefore, for further investigation, statistical analysis was performed.

Puncochar et al. showed that there is a strong linear relationship between the standard deviation of pressure fluctuations and the gas velocity.[12] To examine the validity of this

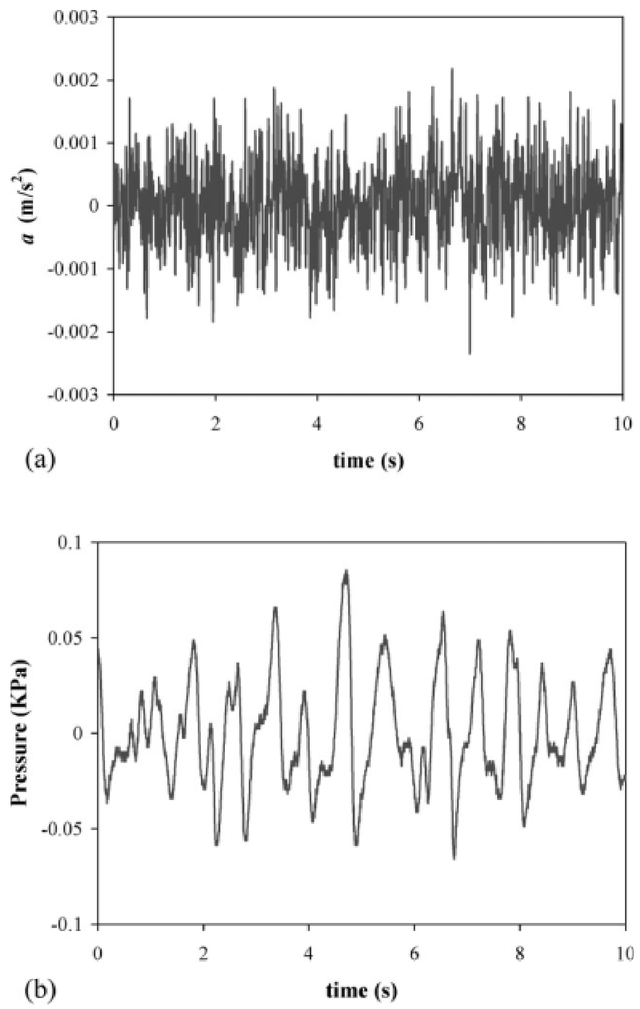

Figure 2. Typical time series signals for 490 μm sand with probe located 5 cm above the distributor (a) vibration and (b) pressure.

technique for vibration signals, experimental data were analyzed by linear regression to check if zero standard deviation corresponds to the minimum fluidization velocity. It should be noted that Puncochar et al. observed that there is nonlinearity between σ_P and U_G at high superficial velocities and recommended using a superficial gas velocity between 1 and 3 times U_{mf} for determining the minimum fluidization velocity by this method.[12] Felipe and Rocha indicated that it is important to determine the appropriate position for the pressure probes.[13] They found that placing the pressure probe close to the gas distributor would introduce significant errors in determining minimum fluidization velocity.

The standard deviations of vibration and pressure fluctuation signals as a function of gas velocity are shown in Figures 3a, b, respectively. As can be seen in these figures, the standard deviation increases with increased superficial gas velocity in both cases. The increase of standard deviation in both vibration and pressure fluctuation signals originates from the increase in bubble size and bubble frequency that occurs at higher gas velocity. As mentioned, Puncochar et al. showed that the standard deviation of pressure fluctuations increases linearly with superficial gas velocity.[12] While Figure 3b confirms such a relationship, Figure 3a illustrates that the same relationship exists with vibration signals.

According to the method of Puncochar et al.,[12] U_{mf} can be determined from the intercept of the linear part of the standard deviation of the pressure fluctuations with the gas velocity axis. Minimum fluidization velocity was determined in this study by the same method, using the vibration signals. The main purpose of this was to evaluate the vibration technique while calculating minimum fluidization velocity. The minimum fluidization velocities obtained by this method are listed in Table 2 for the probe located at 5 cm above the distributor. The values predicted by the correlation of Wen and Yu are also given in this table.[18] It is evident from this table that using the vibration signals provides U_{mf} values considerably closer to the real value compared to using pressure fluctuation signals.

It is worth noting that the trend of the changes of standard deviation for the largest particle size (close to Geldart D) is relatively different than the others (Geldart B) as can be seen in Figure 3a. In fact, before minimum fluidization, standard

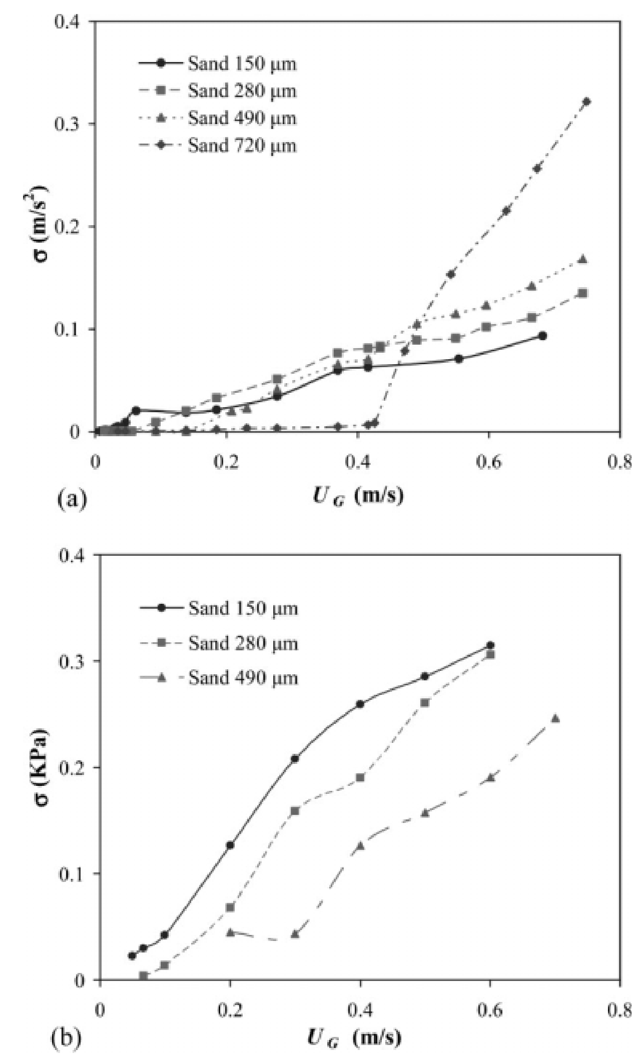

Figure 3. Standard deviation of signals obtained at 5 cm above the distributor (a) vibration and (b) pressure fluctuations.

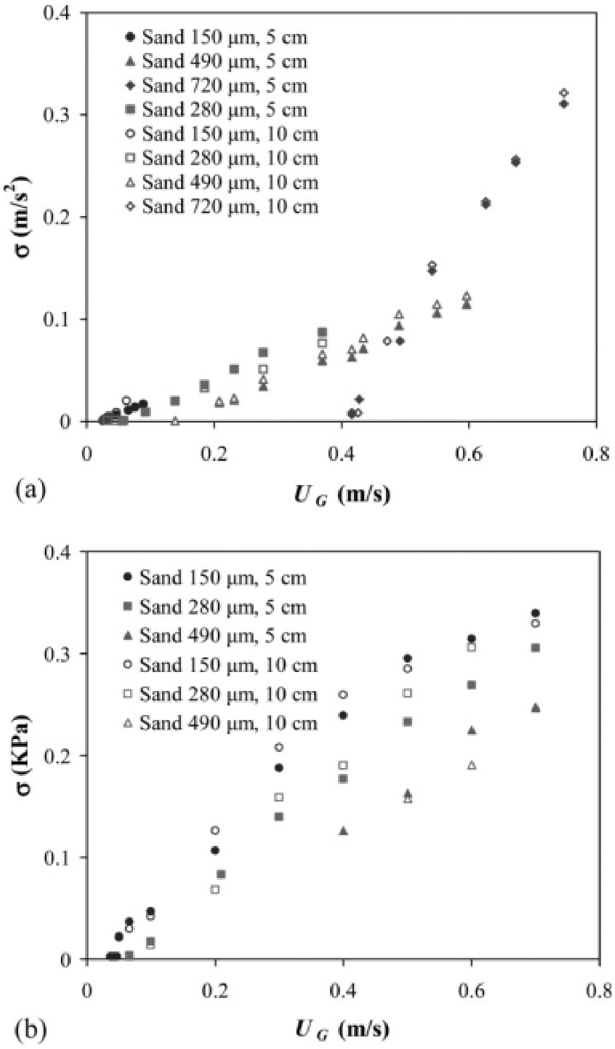

Figure 4. Variation of standard deviation at different probe positions (a) vibration and (b) pressure fluctuations.

deviation of vibration signal is very low which indicated that the particles are more or less motionless at such velocities due to their large size. However, when the bed becomes fluidized, larger bubbles form for the bed of larger particles. These large bubbles pass through the bed vigorously and explode at the bed surface which results in more intense vibration of the bed. This is why the standard deviation of vibration signal of the largest particles increases considerably faster than that of smaller particles. In fact, this trend can be used for determining the type or even size of particles.

It is worth noting that Felipe and Rocha found that for a reliable estimation of U_{mf}, the pressure probe cannot be placed near the air distributor.[13] However, Table 2 reveals that minimum fluidization velocity can be appropriately evaluated from the standard deviation of vibration signals, even if the probe is placed close to the distributor (5 cm above the distributor level). In a fluidized bed, a turbulent zone is formed just above the air distributor both from the air jets and through the formation and coalescence of bubbles in that region.[13] Pressure signals captured close to the air distributor can be affected by this turbulent zone. Nevertheless, the results suggest that the effect of entrance zone is negligible compared to the effect of the first bubble formed in the bed. To examine the effect of probe position on predicting U_{mf}, the variation of standard deviation of vibration and pressure fluctuation signals are plotted in Figures 4a, b for two different positions (5 and 10 cm above the distributor). It can be seen in Figure 4a that estimating the minimum fluidization velocity by the method of Puncochar et al.[12] does not depend on the position of the probe when using accelerometer. In fact, standard deviations of vibration signals at each gas velocity are similar for different probe positions. However, this is not the case for standard deviations of pressure fluctuations in Figure 4b, for which standard deviations at different heights are relatively different. Therefore, in contrast to pressure fluctuations, determining the minimum fluidization velocity from vibration signals is not sensitive to the probe axial position.

The third central moment, or skewness, was calculated for both vibration and pressure fluctuation signals. Variations of skewness with gas velocity are shown in Figures 5a, b for the pressure fluctuation and vibration signals, respectively. It

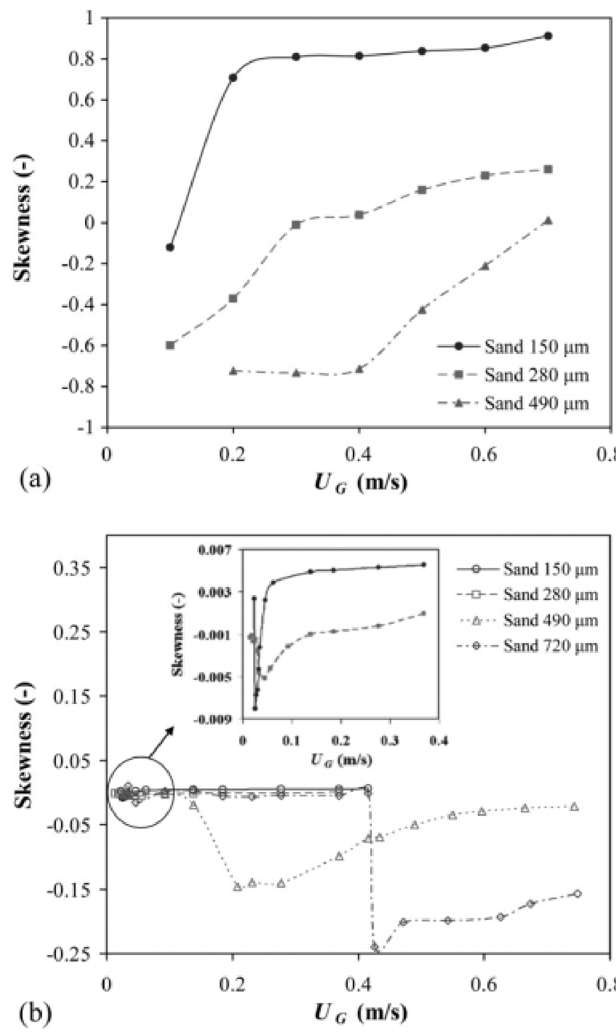

Figure 5. Skewness of signals at 10 cm above the distributor (a) pressure fluctuations and (b) vibration.

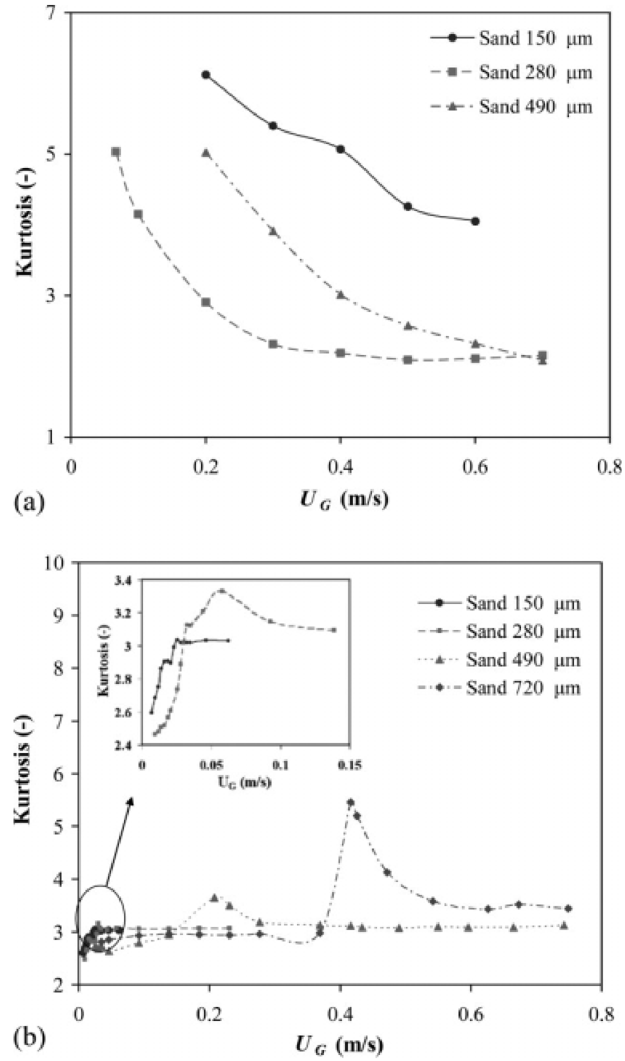

Figure 6. Kurtosis of signals at 10 cm above the distributor (a) pressure fluctuations and (b) vibration.

is evident from Figure 5a that the skewness of pressure fluctuations increases monotonously with an increase in gas velocity. As mentioned earlier, the frequency and size of bubbles increase with increasing gas velocity. Therefore, the distribution of pressure fluctuations extends out toward higher values. Consequently, the skewness of the pressure fluctuations increases with increasing gas velocity. In general, before minimum fluidization velocity there is no change in the skewness, increases sharply after reaching minimum fluidization and levels off at velocities 5 to 9 times U_{mf}. Of course, the level off of 490 μm sand cannot be shown in Figure 5a because of limited gas velocity used in this work.

It is obvious from Figure 5a that it is not possible to estimate the minimum fluidization velocity from the skewness analysis of the pressure fluctuations. However, Figure 5b illustrates that the skewness of the vibration signals exhibits a minimum against U_{G}. It was found that the minimum value of skewness occurs at the minimum fluidization velocity for the particles used in this study. At gas velocities lower than the minimum fluidization velocity, the skewness remains almost unchanged. At minimum fluidization velocity, bubbles are formed in the bed leading to a distinct change in vibration signals. As the gas velocity increases, more bubbles are formed and the probability distribution extends toward positive values because of the increasing amplitude of the vibration signals.

The forth central moment, or kurtosis, was also calculated for vibration and pressure fluctuation signals. The effect of gas velocity on kurtosis of pressure fluctuation and vibration signals in the bed of different sand particles is illustrated in Figures 6a, b, respectively. Figure 6a shows that the kurtosis of pressure fluctuations decreases monotonously with increasing the gas velocity. This trend is opposite to that observed for skewness. The decrease of kurtosis with increasing gas velocity can be attributed to the increase in the size and number of bubbles. Again, it is not possible to estimate minimum fluidization velocity from the kurtosis analysis of pressure fluctuations. However, Figure 6b illustrates that the kurtosis exhibits its maximum value with increasing U_{G} and this maximum occurs at minimum fluidization velocity. Before minimum fluidization velocity, kurtosis does not change considerably and the probability distribution exhibits a flatter peak. Formation of bubbles at the minimum fluidization velocity has a drastic effect on the vibration signals. Consequently, a sharper peak is seen in the probability distribution which causes a higher kurtosis value.

Minimum fluidization velocities calculated from skewness and kurtosis of the vibration signals are listed in Table 2 for all particles used in this work. It can be seen in this table that the minimum fluidization velocities obtained from statistical analysis of vibration signals are very close to the minimum fluidization velocities obtained by the pressure drop measurement. As mentioned earlier, skewness and kurtosis of the pressure fluctuations were not appropriate criteria for determining the minimum fluidization velocity. Figure 7 shows the parity plot of minimum fluidization velocities obtained from the standard method of pressure drop measurement against the other techniques (standard deviation, skewness, and kurtosis of vibration signals) investigated in

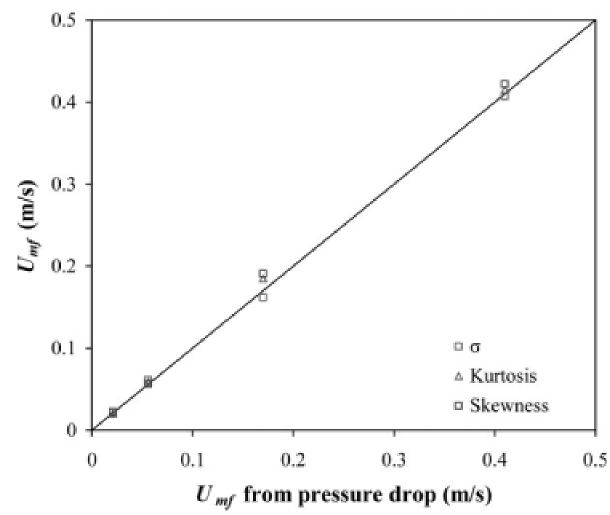

Figure 7. Parity plot of minimum fluidization velocities obtained from statistical analysis against real values.

this study. As seen in this figure, the velocities obtained from the statistical analysis of vibration signals are in good agreement with the experimental values.

As shown earlier, vibration signature technique is comparable with pressure fluctuations. It was shown that in some cases, the vibration signature technique is more sensitive to hydrodynamic changes of the fluidized bed than pressure measurement. Although in this work the vibration technique was applied to velocities close to minimum fluidization velocity, it can be further developed to re-evaluate the hydrodynamics of the fluidized bed. This will provide a better picture of fluidized bed hydrodynamics, which is important due to its application in chemical reactors. It is suggested that this technique can be used in the future to assess the hydrodynamic state of fluidization as a nonintrusive measurement technique.

Conclusion

The minimum fluidization velocity of gas–solid fluidized bed was determined through statistical analyses of vibration signals measured by an accelerometer. Pressure fluctuations were also measured simultaneously by pressure transducer. Previously, the standard deviation of bed pressure fluctuations had been shown to be appropriate for estimating U_{mf}. It was found in this work that there was also a linear relationship between standard deviation of vibration signals and gas velocity by which the minimum fluidization velocity was estimated from the intercept of this line with the gas velocity axis. Minimum fluidization velocities obtained from the standard deviation of vibration signals were in better agreement with the real values than those obtained from pressure fluctuations. It was also found that it is possible to determine minimum fluidization velocity from curves representing the skewness and kurtosis of vibration signals against superficial velocity. However, it was not possible to find the minimum fluidization velocity from the skewness and kurtosis of pressure fluctuations. Results of this work demonstrate that vibration signals can be used to characterize the hydrodynamics of fluidized beds. It is suggested that this technique can be used in the future to assess the hydrodynamic state of fluidization because it is more sensitive to the hydrodynamic changes of the fluidized bed than pressure fluctuations. Moreover, measurement of bed vibrations is a nonintrusive technique that provides more reliable information from the phenomena occurring inside the bed.

Acknowledgements

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Notation

a = acceleration, m/s^2
x_i = amplitude of the time-series signal
$\bar{x}$ = mean value
K = kurtosis
n = length of the time-series signal
S = skewness
U_c = transition velocity at which the standard deviation of pressure fluctuation reaches a maximum, m/s
U_G = superficial gas velocity, m/s
U_k = superficial gas velocity corresponding to the leveling-off standard deviation of pressure fluctuations as velocity increases, m/s
U_{mf} = minimum fluidization velocity, m/s
$U_{m\sigma}$ = minimum standard deviation velocity, m/s

Greek letters

σ = standard deviation
σ_P = standard deviation of pressure fluctuation signal, KPa

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