International Journal of Multiphase Flow 35 (2009) 1011–1016

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Determination of hydrodynamic behavior of gas–solid fluidized beds using statistical analysis of acoustic emissions

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ARTICLE INFO

Article history:
Received 1 February 2009
Received in revised form 20 May 2009
Accepted 30 June 2009
Available online 10 July 2009

Keywords:
Fluidization
Acoustic emissions
Statistical analysis
Bubbles

ABSTRACT

In the processes involving the movement of solid particles, acoustic emissions are caused by particle friction, collision and fluid turbulence. Particle behavior can therefore be monitored and characterized by assessing the acoustic emission signals. Herein, extensive measurements were carried out by microphone at different superficial gas velocities with different particle sizes. Acoustic emission signals were processed using statistical analysis from which the minimum fluidization velocity was determined from the variation of standard deviation, skewness and kurtosis of acoustic emission signals against superficial gas velocity. Initial minimum fluidization velocity, corresponding to onset of fluidization of finer particles in the solids mixture, at which isolated bubbles occur, was also detected by this method. It was shown that the acoustic emission measurement is highly feasible as a practical method for monitoring the hydrodynamics of gas–solid fluidized beds.

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1. Introduction

Fluidized beds have provided an effective means of gas–solid contact in chemical industries. In spite of their advantages, lack of reliable knowledge about the hydrodynamics of fluidized bed reactors has limited their application in large scale units. In some applications, a well defined and stable contact regime is difficult to maintain. For instance, defluidization phenomenon can be reached due to agglomeration when the superficial gas velocity is slightly below minimum fluidization of agglomerates. Thus, if the region where the latter takes place is detected on time, it would be possible to actuate in the fluidization process at the appropriate moment to avoid the defluidization (Parise et al., 2008).

Most investigators have used pressure signals and their fluctuations to determine formation, rise-up and eruption of bubbles (Lu and Li, 1999; Sasic et al., 2006), velocity and size of bubbles (van der Schaaf et al., 2002), minimum fluidization velocity (Parise et al., 2008; Sau et al., 2007), minimum slugging velocity (Lee et al., 2002), regime transition in the bed (Briens and Ellis, 2005; Shou and Leu, 2005; Yang and Leu, 2008; Alberto et al., 2004), gas–solids flow behavior (Wu et al., 2007) and particle size monitoring (Davies et al., 2008). Optical fiber probe measurements and their fluctuations also have been extensively used for measuring the local solids velocity (Ellis et al., 2004; Hatano and Ishida, 1981) and cluster identification (Afsahi et al., 2009) in fluidized beds. These fluctuations can provide valuable information about the hydrodynamics of the beds. Yet in some cases, these methods are not reliable means of measurement since their intrusiveness can alter the local hydrodynamics of the fluidized bed. Therefore, new non-intrusive monitoring systems, suitable for characterizing the bed dynamics, especially under severe, corrosive, reactive and high pressure/temperature conditions are always necessary.

A technique to perform a non-intrusive detection is through the analysis of acoustic emissions (AE). The measurement devices of such a method are applicable to a wide range of process conditions, low costing and reliable to the process being monitored. Moreover, direct contact with the process is not required, allowing real-time, on-line monitoring with little or no intrusion (Boyd and Varley, 2000; Villa Briongos et al., 2006; Abbasi et al., 2009). Acoustic emissions have been used in chemical engineering processes for hydrodynamic characterization and regime transitions in bubble columns (Al-Masry et al., 2007; Ajbar et al., 2009; Al-Masry and Ali, 2007), detection of oversized material in pipe (Albion et al., 2007a), granulation (Briens et al., 2007; Tsujimoto et al., 2000) and coating process (Naelapaa et al., 2007). In the gas–solid fluidized beds, the sounds generated by the friction, collisions and fluid turbulence can provide the *listener* with valuable information on the bed hydrodynamics (Boyd and Varley, 2000). Villa Briongos et al. (2006) investigated the values of frequencies in fluidized beds. They showed that measurement of low frequency passive acoustic emissions analyzed in frequency domain is useful for monitoring gas–solid fluidized bed hydrodynamics. Difficulties in extracting the information from the AE signal have been one

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doi:10.1016/j.ijmultiphaseflow.2009.06.010

possible reason why AE monitoring is not more widespread. Dynamic measurements of various signals extracted from different measurement devises in fluidized beds were analyzed using statistical (Hong et al., 1990; Wilkinson, 1995; Abbasi et al., 2009), fractal (Briens and Ellis, 2005), chaos (Ellis et al., 2003; Chaplin et al., 2004; van der Schaaf et al., 2004; Lin et al., 2001) and wavelet analysis (Wu et al., 2007).

This work highlights the use of AE measuring technique by applying passive acoustic emissions created by a gas–solid fluidized bed as a potentially non-intrusive, real-time monitoring technique to be used in the process control. The main objectives of this study were to test the applicability of acoustic emissions to characterize the hydrodynamics of fluidized beds as well as to investigate the suitability of statistical methods for the analysis of acoustic emission signals.

2. Theory

Statistical analysis in the time domain is a technique which is more commonly employed. This technique, comprising standard deviation, skewness and kurtosis, is very fast and of easy application (Briens et al., 2007; Parise et al., 2008).

2.1. Standard deviation

The standard deviation is a measure of the degree to which the data spreads around an average value and is defined as:

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

where the mean value is calculated from:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n}x_i \tag{2}$$

2.2. Skewness

In the statistics, skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable. Roughly speaking, a distribution has a positive skew (right-skewed) if the right tail is longer and negative skew (left-skewed) if the left tail is longer. Skewness is calculated from:

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

2.3. Kurtosis

Kurtosis, or the fourth moment, is a measure of the relative peakedness of the distribution. Kurtosis is calculated by:

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

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 (Albion et al., 2006, 2007a; Dash et al., 2008).

3. Experiments

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 (see Fig. 1). The whole system was electrically grounded to minimize electrostatic effects. Air at room temperature entered into the column through a perforated plate distributor with 435 holes of 7 mm triangle pitch while its flow rate was measured by a rotameter. A cyclone, placed at the column exit, returned the entrained solids back to the bed. Sand particles with mean sizes of 167, 187, 230, 356 and 560 μm and particle density of 2640 kg/m^3 were used in the experiments. Their size distribution and minimum fluidization velocity determined by bed pressure drop method are shown in Tables 1 and 2, respectively. The experiments were carried out at different bed heights (L/D = 0.5, 1, 1.5) and were repeated three times at the same operating conditions to ensure the reproducibility of the sampled signals.

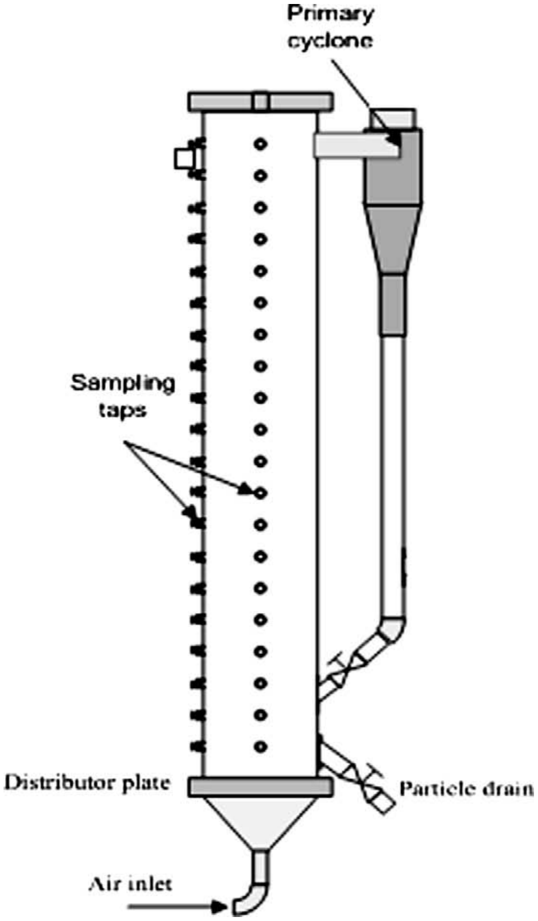

Fig. 1. Schematic of the fluidized bed.

Table 1
Size distribution of sand particles used in this work.

d_{pi} (mm)	Weight fraction				
	Sand I	Sand II	Sand III	Sand IV	Sand V
1	0	0	0	0	0.04
0.85	0	0	0	0	0.20
0.71	0	0	0	0	0.22
0.5	0	0.01	0	0	0.36
0.42	0	0.01	0.08	0.60	0.13
0.355	0	0	0	0	0
0.3	0	0.16	0.44	0.38	0.04
0.25	0	0.11	0.10	0	0
0.18	0.64	0.50	0.27	0.02	0.01
0.15	0.35	0.14	0.08	0	0
0.125	0.01	0.05	0.02	0	0
0.106	0	0.02	0.01	0	0
d_p (mm)	0.167	0.187	0.230	0.356	0.560

Table 2
Minimum fluidization velocity (m/s) of sand particles at $L/D = 1.5$.

d_p (μm)	From bed pressure drop	From Puncochar et al. (1985)	From standard deviation	From skewness	From kurtosis
167	0.03	0.015	0.028	0.03	0.032
187	0.037	0.018	0.035	0.032	0.034
230	0.056	0.026	0.052	0.042	0.042
356	0.13	0.038	0.12	0.11	0.12
560	0.282	0.093	0.21	0.21	0.21

A Bruel and Kjær free-field microphone type 4190 with sensitivity of 50 mV/Pa was used to record the acoustic emission. The microphone was located above the bed surface (in the freeboard), 68 cm from the gas distributor, in order to reduce the noise due to impact of particles. Also, it was desired to test this technique non-intrusively. Of course, different locations for the microphone, including inside the dense bed, outside the wall and in the freeboard, were tested and it was observed that only amplitude of waves would change by changing the location of the microphone but not the locations of the peaks. The microphone produced analogue signals that were conditioned and converted to digital using the B&K PULSE system along with 3560C hardware. According to Wentzell and Wade (1989) the signals of acoustic emission from chemical reaction are distributed mainly in high frequency ranges such as 50 kHz to 1.5 MHz. Although no chemical reaction was carried out in this study, at first the sampling frequency was set to 65 kHz to make sure that no information is lost during data acquisition. 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 (Oppenheim and Willsky, 1997).

4. Results and discussion

A Typical acoustic signal, recorded by the microphone is shown in Fig. 2. The fluctuations may represent three types of basic sources of passive acoustic emission in the fluidized bed: (i) particle–particle or particle–wall collision (impact sounds), (ii) particle–particle or particle–wall friction (friction sound) and (iii) air turbulence (aerodynamic sound) (Naelapaa et al., 2007; Albion et al., 2007b; Tsujimoto et al., 2000). Apparently, it may not be possible to extract reliable information directly from the raw signals. Therefore, for further investigation, statistical analysis was performed.

The most common method used by many researchers is the study of the standard deviation of the time series which is a measure of the degree to which the data spreads around an average value. The change in amplitude of the time series with operating condition has been of interest for characterization of fluidization regimes (Parise et al., 2008). Some researchers such as Parise et al. (2008) and Yang and Leu (2008) used this analysis to determine the minimum fluidization velocity. Puncochar et al. (1985) proposed a methodology to determine the minimum fluidization velocity based on the relationship between the gas velocity and standard deviation of pressure fluctuations. It should be noted that Puncochar et al. (1985) 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.

Standard deviation of the acoustic signals for 167 μm sand is illustrated in Fig. 3. As the gas velocity increases, so increases the number of flowing bubbles, thus, their sound level. Therefore, the standard deviation of the acoustic signal intensifies with increasing the gas velocity. Similar to the method of Puncochar et al. (1985), U_{mf} was determined from the intercept of the linear part of the standard deviation of the acoustic signals with the gas velocity axis. The minimum fluidization velocities obtained by this method are listed in Table 1. It is evident from this table that these velocities are considerably lower than the minimum fluidization velocity determined by the bed pressure drop. Therefore, the standard deviations were studied more thoroughly. As can be seen in Fig. 3, at low velocities that the bed is still fixed, no sound can be detected from the particles and the standard deviation of the acoustic signals is nearly zero. By increasing the gas velocity, standard deviation starts to increase sharply at 0.016 m/s and the first transition can be observed at this condition. This velocity is lower than the minimum fluidization velocity determined from bed pressure drop data (see Table 1). However, formation of isolated bubbles was observed visually in the experiments at this velocity. Therefore, this velocity can be corresponded to the start of minimum fluidization of the powder, i.e., minimum fluidization of smaller particles in the mixture. In fact, the smaller particles reach their minimum fluidization sooner than the larger ones and produce bubbles before the whole bed becomes fluidized. In other words, this velocity is the initial minimum fluidization velocity of the powder. Beyond this point, the standard deviation increases up to 0.023 m/s, then it decreases leading to the second transition

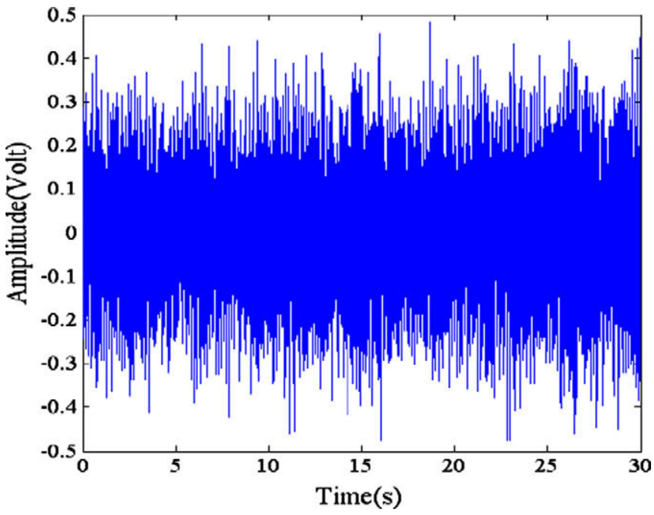

Fig. 2. Typical time series sound signal for 230 μm sand.

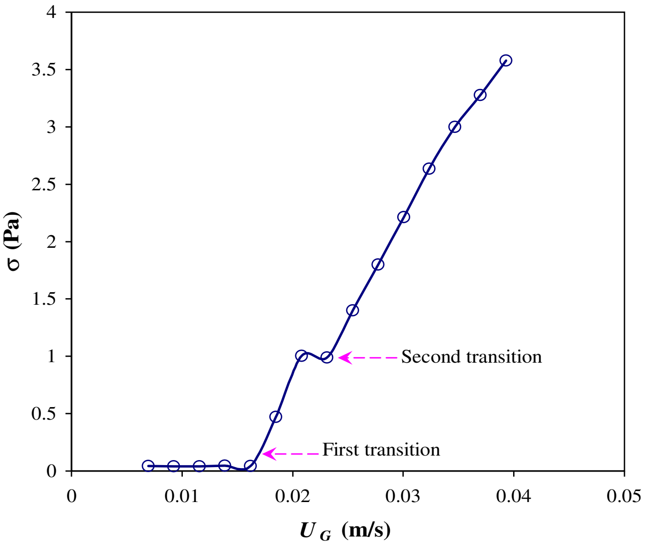

Fig. 3. Variation of σ_p with superficial velocity for 167 μm sand and $L/D = 0.5$.

point. At this velocity, the whole bed is fluidized, thus, the second transition occurs at minimum fluidization of the powder. Table 1 confirms this conclusion.

Influence of the bed height on the first and second transition points is shown in Fig. 4 for 230 μm sand. At $L/D = 0.5$, the two transition points can be seen at 0.028 and 0.032 m/s, respectively. With an increase of bed height to $L/D = 1$, small particles cannot become fluidized separately and the initial bubbles start to show up at a higher gas velocity. As a result, both transition points increase to 0.035 and 0.037 m/s, respectively. At moderately large bed height, i.e., $L/D = 1.5$, the bubbles start to form at higher gas velocity, where the whole bed (or most of particles in the mixture) becomes fluidized. Consequently, only one transition point can be observed at 0.052 m/s which is closest to the actual minimum fluidization velocity according to Table 1.

In order to demonstrate the effect of bed height on first and second transition points, these values at various bed heights are shown in Fig. 5 for two different sands. As can be seen in this figure, by increasing the bed height, these two points become closer to each other and become identical at high enough aspect ratio. In other words, initial minimum fluidization can be observed at shallow beds. In the deep beds, only final minimum fluidization can be observed.

The third central moment, or skewness, of the acoustic emission signals was also evaluated. This is shown against gas velocity in Fig. 6 for different initial bed heights. At the gas velocities lower than the minimum fluidization, the skewness remains almost unchanged. At the initial minimum fluidization, isolated bubbles are formed, leading to a distinct change in the acoustic emission signals. The skewness exhibits a minimum (against gas velocity) at this point. As the gas velocity reaches the minimum fluidization, the skewness exhibits another minimum. Afterwards, the distribution extends towards positive values because of increasing amplitudes of the acoustic emission signals. Like what was observed in the case of standard deviation, with increasing the bed height, the two transition velocities become closer and at $L/D = 1.5$ only one transition point can be seen at minimum fluidization. It is worth mentioning that Vial et al. (2000) also used skewness for analyzing the pressure fluctuations but they were not able to obtain any useful information out of its trend.

The fourth central moment, or kurtosis, was also calculated for the acoustic emission signals. The effect of gas velocity on kurtosis of the acoustic emission signals in the bed of different sand particles is illustrated in Fig. 7. As can be seen in this figure, the kurtosis also exhibits two maximums against gas velocity for smaller particle sizes (167, 187 and 230 μm). The first maximum corresponds to the initial minimum fluidization and the second one occurs at the minimum fluidization velocity of the mixture. For the larger particles (356 and 560 μm), the bubbles form only beyond minimum fluidization velocity. That is why only one maximum is seen in the kurtosis curve of large particles.

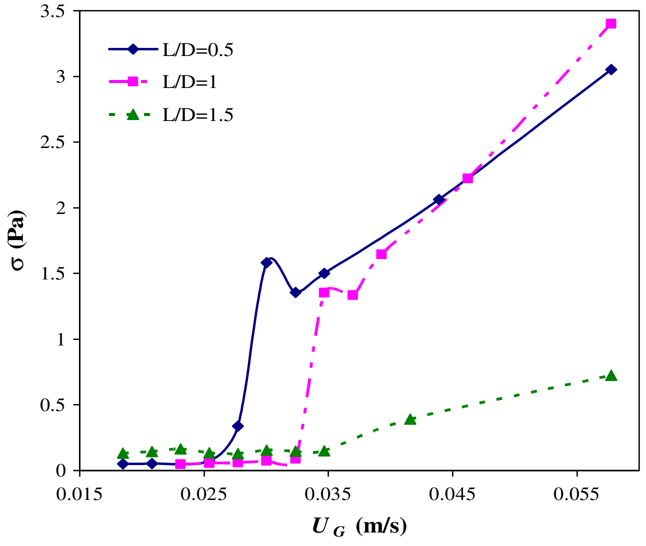

Fig. 4. Variation of σ_p with superficial velocity for 230 μm sand.

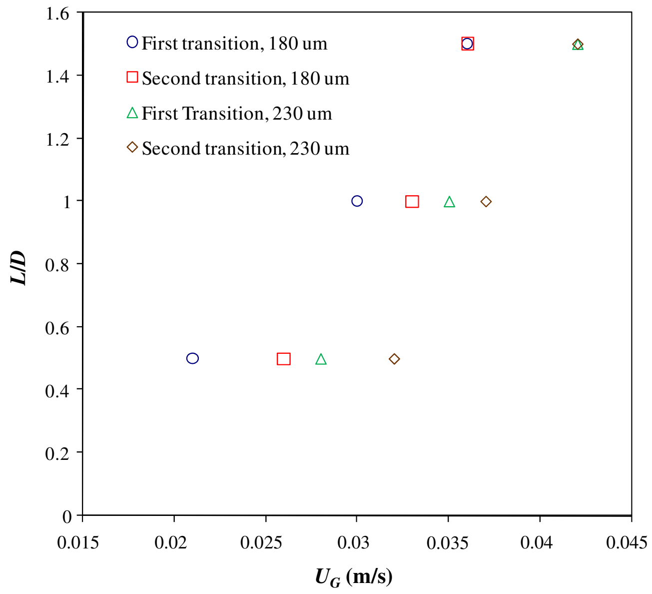

Fig. 5. Comparison of first and second transition points for 187 and 230 μm sands.

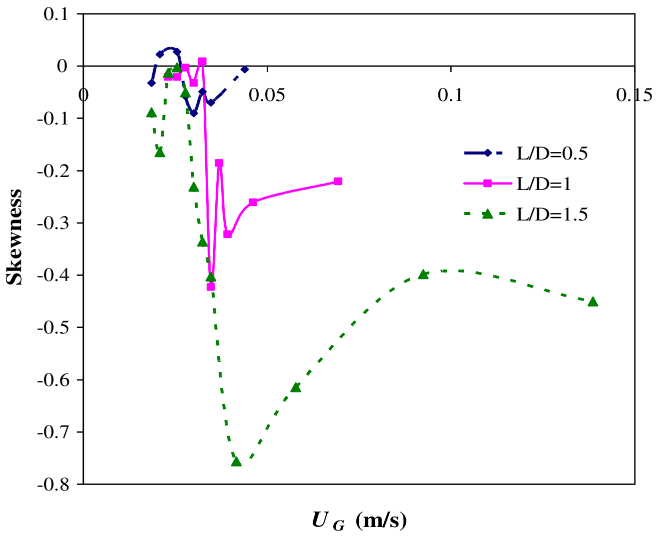

Fig. 6. Skewness of sand 230 μm sound signals at different bed heights.

Fig. 8 illustrates the kurtosis of 230 μm sand at different initial bed heights. As mentioned earlier, with the increase of bed height, the weight of bed increases and even the smaller particles cannot become fluidized easily. Therefore, no single bubble may appear before minimum fluidization in deep enough beds; creation of bubbles occurs only after minimum fluidization. As a result, only one maximum can be observed in the kurtosis of the acoustic emission signals.

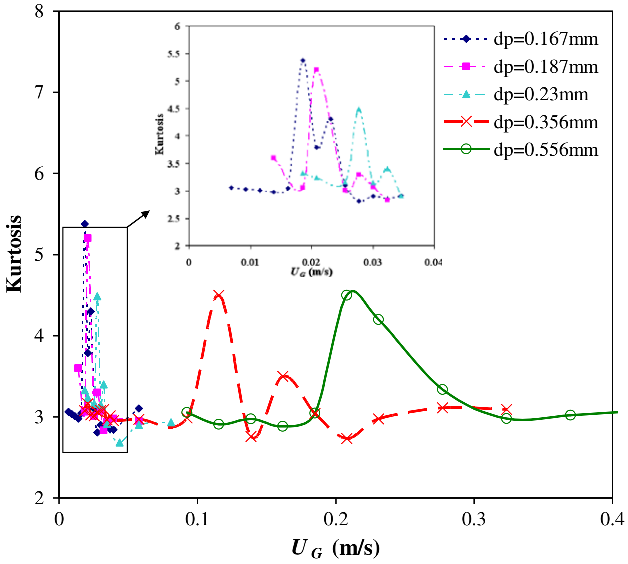

Fig. 7. Kurtosis of sound signals at $L/D = 0.5$.

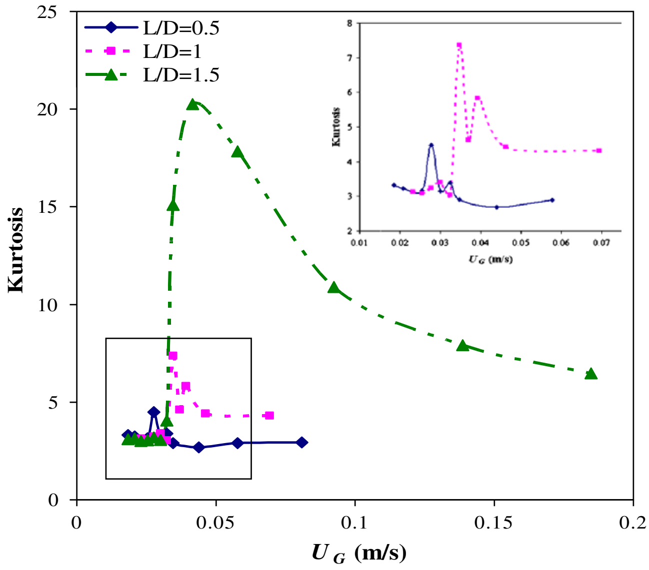

Fig. 8. Kurtosis of sand 230 μm at different bed heights.

5. Conclusion

In this study, the hydrodynamic state of the gas–solid fluidized bed was determined by statistical analysis of the acoustic emission signals measured by a microphone. Plotting the standard deviation of the acoustic signals against gas velocity showed two transition points in the fluidization of gas–solid mixture. The first transition point corresponds to initial fluidization velocity (i.e., fluidization of small particles in the mixture at which isolated bubbles occur) and the second transition point corresponds to the full minimum fluidization of the bed. It was shown that by increasing the bed height, the velocities of these two transitions merge together. In other words, at high enough aspect ratios, the initial fluidization fades and only fluidization of the whole bed can be observed. Similar information can be extracted from variations of skewness and kurtosis of acoustic emission signals against superficial gas velocity. Results of the present work demonstrate that acoustic signals can be used to characterize the hydrodynamics of fluidized beds efficiently.

Acknowledgement

The authors thank Mr. Ali Shahsavari of NVA labs, School of Mechanical Engineering, University of Tehran, for his help in data acquisition.

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