Effect of internal tubes on the flow structures in gas-solid fluidized beds

J Gubis\textsuperscript{1}, H R Norouzi\textsuperscript{2}, N Mostoufi\textsuperscript{2*}, R Zarghami\textsuperscript{2}

\textsuperscript{1}Department of Chemical Engineering, Institute of Chemical Technology, Prague, Czech Republic.
\textsuperscript{2}Process Design and Simulation Research Centre, School of Chemical Engineering, College of Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran.

* Corresponding author: mostoufi@ut.ac.ir

Abstract. The influence of internal tubes present in the fluidized bed on its hydrodynamic behavior was examined in this study. One tube was completely immersed in the bed of 650 μm glass beads at 10 cm above the air distributor in the 15 cm inner diameter fluidized bed column of aspect ratio 1. The pressure fluctuations signal was collected over 300 s and was consequently analyzed by the both statistical and wavelet analyses. The results showed that the presence of tube within the bed suppresses the occurrence of macro-scale phenomena like formation of large bubbles and its stability and supports the meso-structures such smaller bubbles, voids and clusters. It leads to an earlier onset of bubbling flow regime as well as turbulent flow regime. The observed minimum bubbling velocities were compared with data in literature and were found in a good agreement with them.

Keywords. fluidized bed, pressure fluctuations, bed internals, hydrodynamic behavior

1. 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 characteristics of the fluidized bed. Many investigators have used pressure signals [1, 2] and their fluctuations to determine and distinguish between phenomena occurring within the bed like formation, movement, coalescence and break-up of bubbles, slugging etc. [3-6]. Various analysis methods of the pressure signals have been developed, for both time and frequency domains, such as wavelet analysis, Fourier transform, chaos analysis etc., to extract the necessary information about the hydrodynamic behavior of the fluidized bed, namely minimum fluidization velocity, regime transition velocities, bubble characteristics or to estimate the dominant phenomena in the bed [6-8].

Wavelet transform analysis was utilized for non-linear and transient time series data for a better resolution in the frequency domain [9]. For example, this method can be used to characterize regime transition from minimum fluidization to bubbling and from bubbling to turbulent fluidization [9].

Traditionally, statistical analyses have been used to determine hydrodynamic changes and fluidization quality of the bed [3, 5 11]. Statistical measures that can be used to analyze the signals include standard deviation, skewness, and kurtosis. Puncochar et al. [5] and Felipe and Rocha[1] 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 [12]. They found that the maximum point in the kurtosis and the minimum point in the skewness correspond to transition velocities. Since the fluidization process is very complex, any change of conditions will lead to change of the hydrodynamic behavior of the bed, e.g. by addition of a fixed obstacle into the bed for the sake of the enhancement of heat transfer area.

The main objective of this study was to recognize the effects of internals attached into the bed on the hydrodynamic characteristics of the fluidized bed. The pressure signals of the bed were recorded and subsequently analyzed using wavelet analysis tools and statistical analysis and the results were compared with literature data.

2. Experiments
The experimental setup is shown in Figure 1 schematically. The experiments were carried out in a gas-solid fluidized bed column made of a Plexiglas pipe of 15 cm inner diameter and 2 m height. The whole system was electrically grounded to minimize electrostatic effects. Air at room temperature entered the column through a perforated plate distributor with 0.75 mm holes on 8 mm triangular pitch. Air flow rate was controlled by a digital mass flow meter. The superficial air velocity range was 0 - 2 m/s. The height of the static bed was set to 15 cm (aspect ratio of 1). Glass bead particles with density of 2525 kg/m$^3$ and 670 $\mu$m mean diameter were used in the experiments. A 1-inch cylindrical tube was inserted through the whole column diameter, located at 10 cm above the distributor, thus it was completely immersed in the bed. Pressure fluctuations signal was collected over 300 seconds at the sampling frequency of 400 Hz. The frequency was considered to be high enough to avoid any information loss since the frequency of observed phenomena within the bed reaches 20 Hz at the maximum [13].

![Figure 1. Experimental setup scheme](image)

3. Methods of data analyses
The obtained differential pressure signals were analyzed by using both the wavelet analysis tools and statistical analysis (standard deviation, skewness and kurtosis). Using the wavelet analysis, the decomposition level was set to 8, thus the signals were decomposed into nine sub-signals, where
approximation levels a1-a8 represent low frequency components and detailed coefficients D1-D8 represent high frequency components [14]. By recombining the sub-signals, three different scales belonging to different flow structures were extracted from the original signals [8]. The micro-scale, represented by the D1 to D4 sub-signals with frequency more than 10 Hz is related to particle interactions. The meso-scale is represented by the D5 and D6 sub-signals and corresponds to small bubbles, clusters and voids in the bed in frequency range 3-10 Hz. The macro scale represents large bubbles and bubble eruptions on the bed’s surface and slugging and consists of D7, D8 and a8 sub-signals. After that the energies of the flow structures were computed by the following equations

\[ E_{ia} = \sum_{i=0}^{n} |a_i(t)|^2 \]  

(1)

\[ E_{id} = \sum_{i=0}^{n} |D_d(t)|^2 \]  

(2)

where \( a_i(t) \) and \( D_d(t) \) represent the approximation and detail sub-signals. Finally, the total energy of the signal is expressed:

\[ E = E_{ia} + \sum_{i=0}^{n} E_{id} \]  

(3)

Statistical analysis of the pressure signal was applied to justify consistency of results obtained from wavelet analysis. Standard deviation, skewness and kurtosis analyses were used. Disadvantages of the statistical analysis lie in the fact that it does not work with de-noised signal and does not allow to extract specific flow structure in the bed being predominate. The standard deviation is defined as:

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

(4)

Skewness, the measure of asymmetry of data distribution function is defined as:

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

(5)

and kurtosis, the measure of the sharpness of the distribution function as:

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

(6)

### 4. Results and discussion

The energies of different flow structures were computed and compared for the experimental setups containing either none or one tube. The energies of the pressure signals are depicted as a function of air velocity in the Figure 2. Obviously, the presence of an internal supports an earlier onset of bubbling regime and also the onset of turbulent flow regime. The minimum bubbling velocities, \( U_{mb} \), were determined as 0.29 m/s (system with no internals) and as 0.26 m/s (system with one internal tube). It was found to be in a good agreement with the literature [15], which proposes the \( U_{mb} \) to be 0.286 m/s. The maximum in the energy demarks the onset of turbulent flow regime [13, 16]. While for the plain bed the maximum occurs at the velocity near to 1.9 m/s, it is shifted to 1.2 m/s by insertion of one tube.
The changes in energy of the flow structures in the bed caused by the insertion of an internal as a function of the air velocity are shown in Figure 3. The energy of the macro structures decreases with the insertion of tube while the energy of meso structures increases. It shows that the presence of the internal suppresses the formation and flow of large bubbles and on the other hand supports formation of smaller bubbles, voids and clusters. It was also observed visually in the bed. The energy of the micro structures remains mostly unchanged and can be considered as independent on the presence of the internals.

The contribution of energy of different flow structures is shown in the Figure 4 for the experiments with no tubes present in the bed. In the velocities lower than the minimum fluidization velocity the major percentage of energy belongs to the micro structures – particle-particle and particle-wall interactions. The major change in the value of contribution of the macro structures corresponds to the flow regime transition (onset of fluidization). From that point, the contribution of micro structures is
almost negligible and the major percentage of energy is held by the macro and meso structures – formation, rise and break-up of the bubbles, voids and clusters.

![Graph showing Contribution of energy of each structure to the total energy around minimum fluidization velocity](image1)

**Figure 4.** Contribution of energy of each structure to the total energy around minimum fluidization velocity

The comparison of results of both statistical and wavelet analyses is shown in Figure 5. There is conformity in the trends for experiments with one tube present in the bed. The trend lines reach their maximum, denoting the onset of turbulent flow regime in the bed, at the same air velocity in case of one tube inserted to the bed. However, this trend was not observed in case of bed without any tube. The earlier onset of turbulent in presence of internals cannot be therefore reliably justified and further investigations are needed.

![Graph showing Comparison of the analysis methods](image2)

**Figure 5.** Comparison of the analysis methods
The skewness as function of velocity is depicted in Figure 6. It shows the same influence of an internal on the bed hydrodynamic behavior – the shift of reaching the zero value of skewness corresponds to the transition between the structures in the bed [17], while the internal is present in the bed. In the Figure 7, the kurtosis as function of the air velocity shows same trend, when it reaches its minimum at lower velocities, which corresponds to the different flow structures in the bed.

5. Conclusions
The influence of internals present in the fluidized bed on the hydrodynamic behavior has been studied. The results show that the presence of tube within the bed suppresses the occurrence of macro-scale phenomena like formation of large bubbles and its stability and supports the meso-structures such smaller bubbles, voids and clusters. It leads to an earlier onset of bubbling flow regime as well as turbulent flow regime. The observed minimum bubbling velocities were compared with data in literature and were found in a good agreement with them. Future work will be focused on experiments with several tubes within the bed and experiments with particles with weaker electrostatic effects.
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