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Flow structure characterization in conical spouted beds using pressure fluctuation signals

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ABSTRACT

Characteristics of the hydrodynamics of conical spouted beds were revealed by analyzing pressure fluctuation signals in the frequency domain. Experiments were carried out in spouted beds with three different cone angles (30°, 45°, 60°) and high density spherical particles ($\rho_p = 6050$ kg/m^3) with diameters of 0.5 or 1 mm. Different hydrodynamic structures in the movement of solids were identified by examining pressure fluctuations of the bed in the frequency domain. Peaks in the power spectral density of pressure fluctuations were observed corresponding to movement of bulk of solids (low frequency, less than 5 Hz), particle transport in the spout (medium frequency, between 5 and 15 Hz) and clustering and motion of clusters throughout the bed (high frequency, between 15 and 130 Hz). Axial movement of solids and pulsation motion of spout peripheries each exhibits a distinct peak in the medium frequency zone. It was shown by the frequency domain analysis of pressure fluctuations that solids are more mobile in annulus of a bed of smaller diameter particles and there is more effective lateral solid transfer from the annulus to the spout when the cone angle is smaller.

1. Introduction

Spouted beds are gas–solid contactors in which particles are thrown up by a high velocity flow of gas through a small orifice at the center of the base of a column. These contactors provide intense gas–solid contact for large and dense particles (i.e., Geldart group D particles) for which conventional fluidization is not possible or difficult to achieve. Spouted beds have been successfully used in various processes such as drying of beans, slurries and pastes, granulation, coating of particles, gasification, pyrolysis and combustion [1].

A conventional cylindrical spouted bed is a cylindrical column with a conical base and the bed material fills a significant portion of the cylindrical section. On the other hand, in a conical spouted bed, the cylindrical section merely acts as a freeboard and the static bed height does not exceed the height of the conical section. One of the main cited advantages of conical spouted beds is short gas residence times with narrow distribution [2]. Successful applications of conical spouted beds include chemical vapor deposition, particle coating, drying and recently, biomass, waste plastic and scrap tire pyrolysis [2–5].

There are considerable differences between the hydrodynamics of conical and conventional cylindrical spouted beds. Empirical correlations for predicting the minimum spouting velocity, spouting bed pressure drop and peak pressure drop in cylindrical spouted beds do not generally work for conical spouted beds. Due to the conical geometry, the lateral (radial) variation of the pressure is more pronounced and the geometrical design requirements (inlet diameter-to-cone bottom diameter ratio, minimum cone angle, inlet diameter-to-particle diameter ratio) are more stringent compared to conventional cylindrical spouted beds [2].

Studies on the hydrodynamics of conical spouted beds have mostly concentrated on minimum spouting velocity and time-averaged bed pressure drop determination as well as measurement of velocity and concentration of particles using optical fiber probes [2,6–15] revealing salient characteristics of this type of gas–solid contactor. On the other hand, pressure fluctuations obtained from a gas–solid system also reflect hydrodynamic status of the system from which useful information about the gas–solid flow structure can be extracted. In the literature, the analysis of pressure fluctuation signals with various techniques (mainly statistical, frequency and chaos analysis) has been used to investigate mainly the hydrodynamics of bubbling and circulating fluidized beds. In bubbling fluidized beds, pressure signals and their fluctuations are known to originate from the flow of the gas through the bed, formation, rise and eruption of bubbles as well as movement of solids and particle–particle and particle–wall collisions [16]. Identifying effect of each of the above phenomena on pressure fluctuations requires proper and rather complex analysis of pressure signals [17,18]. Nevertheless, Johnson et al. [19] grouped these phenomena in gas–solid bubbling fluidized beds into three different structures: macrostructure (with scale of bubbles), mesostructure (with scale of clusters) and microstructure

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Table 1
Major pressure fluctuation signal analysis studies in conventional cylindrical and conical spouted beds.

Study	Bed geometry	Dimension, cone angle	Bed material	Analysis methods
Xu et al. [20]	Conventional cylindrical	80 mm ID ($\gamma = 60°$) 120 mm ID ($\gamma = 60°$)	Glass beads ($d_p = 1.42–1.88$ mm, $\rho_p \cong 2500$ kg/m^3) Silica gel ($d_p = 1.66$ mm, $\rho_p = 720$ kg/m^3)	Statistical, spectral
Oliveira et al. [21]	Conventional cylindrical (half)	80 mm ID ($\gamma = 60°$)	Glass beads ($d_p = 1.2, 2.4$ mm, $\rho_p = 2500$ kg/m^3)	Statistical, mutual information theory, spectral, Hurst's rescaled range method
Marreto et al. [22]	Conventional cylindrical	140 mm ID ($\gamma = 60°$)	Glass beads ($d_p = 2.6$ mm, $\rho_p = 2500$ kg/m^3)	Spectral
Sari et al. [23]	Half conical	150 mm ID ($\gamma = 30°$)	Yttria-stabilized zirconia (YSZ) particles ($d_p = 1$ mm; $\rho_p = 6050$ kg/m^3)	Spectral
Mollick et al. [24]	conical (2D, 3D)	60 mm ID ($\gamma = 60°$)	yttria-stabilized zirconia (YSZ) particles ($d_p = 0.5–0.9$ mm; $\rho_p = 6050$ kg/m^3)	statistical, spectral

(with scale of particles) based on the trends observed in the power spectral density function (PSDF) of pressure fluctuations in the frequency domain.

As far as the spouted beds are concerned, the number of pressure fluctuation signal analysis studies has been very limited as seen in Table 1. Xu et al. [20] performed a statistical and frequency analysis of in-bed pressure data obtained from two different size spouted beds. Since the pressure data were obtained from the conical and cylindrical sections of the spouted bed separately, peculiar characteristics of the conical section could also be identified. In the cylindrical section, the standard deviation of the pressure fluctuation signals increased with superficial gas velocity with an abrupt jump at the minimum spouting velocity. The trend in the conical section was similar, however, respective jump was not pronounced as much. The frequency analysis was based on the PSDF obtained from the fast Fourier transformation (FFT) of the pressure fluctuation signal. In shallow beds, the PSDF showed a wide band distribution without a dominant frequency. In deep beds, the dominant frequency, which was insensitive to particle properties, gas velocity and bed geometry, was found to be in the range of 6–8 Hz, both in the stable and unstable spouting regimes.[1] Oliveira et al. [21] analyzed the pressure fluctuation data obtained from a semi-cylindrical (half) spouted bed using statistical analysis, mutual information theory, spectral analysis and Hurst's rescaled range method. Their spectral analysis revealed a dominant frequency around 10 Hz at the minimum spouting velocity and in the stable spouting region. Marreto et al. [22] obtained a dominant frequency in the range of 6–8 Hz, similar to Xu et al. [20] and Oliveira et al. [21].

In conical spouted beds, our previous work indicated a dominant frequency of 12 Hz in the stable spouting region with high density zirconia particles [23]. This frequency was shown to drop to 9 Hz in the jet spouting regime. The dominant frequency was attributed to the frequency of the particle motion passing through the spout. The jet spouting (or dilute spouting) regime is a peculiar characteristic of conical spouted beds obtained as the superficial gas velocity is increased well beyond the minimum stable spouting velocity. With the same particles, Mollick et al. [24] obtained a dominant frequency around 20 Hz in the spouting regime. They also stated that the pressure fluctuations originated from the particle–particle and gas–particle interactions in the spout.

Another aspect of the bed pressure fluctuations is the possible determination of the minimum spouting velocity using standard deviation. The classical approach to determine the minimum spouting velocity is to use the time-averaged bed pressure drop versus superficial gas velocity data as the velocity is increased and decreased (velocity ascending or descending processes) [24]. Less common but possibly an alternative approach is the use of the standard deviation of pressure fluctuations [20,21]. This method is also used in this work and results are compared to values determined based on time averaged bed pressure drop measurements in our previous publication with high density particles [23].

As can be inferred from the literature, the analysis and the interpretation of the pressure fluctuation data obtained from conical spouted beds are far from complete. The information on the origins of the pressure fluctuations has not been fully established and the link between the frequency spectrum and the corresponding physical flow phenomena in the bed has not been understood clearly. Therefore, the aim of this work is to focus on the PSDF of pressure fluctuations of conical spouted beds to obtain more detailed insight into the hydrodynamics of these contactors. Specifically, it has been tried to identify various flow structures in spouted beds based on the trends observed on the PSDF. The discrete short time Fourier transform (STFT), which is a windowed version of the discrete Fourier transform, was used in the present study. This technique enables the time–frequency analysis of a sampled signal and provides a better resolution in both time and frequency domains. As a result, information can be better extracted from the PSDF compared to the ordinary Fourier transform. Experiments were carried out at various cone angles, particle sizes, initial bed heights and inlet gas velocities to support the conclusions in a wide range of operating conditions.

2. Materials and methods

2.1. Experimental set-up

The experimental data were obtained in three full circular ($\gamma = 30°, 45°, 60°$) and two half circular ($\gamma = 30°, 45°$) conical spouted beds made of polyoxymethylene (also known as Delrin) which is an excellent thermoplastic that can withstand the continuous impact of hard zirconia particles without significant erosion. A schematic diagram of these units is given in Fig. 1 and their geometric parameters as well as operating conditions are presented in Table 2. In this table, the minimum external spouting velocity corresponding to each operating condition is also presented based on our earlier publication [23].[2] The inlet gas velocity is defined based on the gas inlet diameter, D_o (volumetric flow rate divided by the inlet area).

Spherical yttria-stabilized zirconia (YSZ) particles ($d_p = 0.5$ and 1 mm; $\rho_p = 6050$ kg/m^3) were used in the experiments. Compressed air at ambient temperature was used as the spouting gas. The compressed air was supplied from a screw type compressor operating with a supply pressure of 8 bar at a maximum flow rate of 0.05 m^3/s. Two air tanks of 30 L in volume were placed in series between the

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[1] At this point, it is imperative to note that unstable spouting refers to intermittent formation and collapse of the internal spout and occurs once the minimum spouting velocity is exceeded. As the superficial gas velocity is further increased, the instability ceases and stable spouting begins. The velocity corresponding to the onset of stable spouting can be referred as minimum stable spouting velocity.

[2] Simply “minimum spouting velocity”. The word “external” is used here and also in the literature to emphasize the breaking up of the upper bed surface by the spout gas flow.