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Spectral analysis: A Contribution to Control Strategy in Spouted Bed

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The stability of fluid dynamics regime is one of the most desired objectives to ensure the good performance of processes in spouted bed equipment. However, the major problem in these processes is the lack of a control variable with fast response and easy acquisition towards a control strategy in closed loop that could guarantee operation under a condition of stable spouting. The aim of this work was to study and evaluate the behaviour of pressure fluctuation signals and their power spectra in spouted bed as a control and monitor variable. The spectral alterations caused by the change in the mechanics and kinetics of particles were compared with visual observations to identify different phenomena that occur in each fluid dynamic regime. Three variables were monitored: dominant frequency, dominant amplitude and standard deviation of pressure fluctuation signals. Glass beads were used as inert particles and air 343 K as the spouting gas. This paper showed that the dominant frequency, dominant amplitude and standard deviation of pressure fluctuation were variables that show operation range well defined to stable spouted, internal spouted and fixed bed regimes. The three variables demonstrated to be useful to identify the transition regimes or as control variables for maintaining the system in stable spout operation.

1. Introduction

Spouted bed was initially developed for drying wheat, however it has been significantly used as others unit operations, with an emphasis in drying pastes and slurries, granulation and coating, mainly in the chemical, food, pharmaceutical and agricultural industries (Epstein and Grace, 2011). The main advantages of this equipment are the high rates of heat and mass transfer, good particles movement, low cost of construction and operation (Freire *et al.*, 2009). However, because of operating conditions, it is difficult the maintenance of a stable regime resulting in fluid dynamic instabilities, which are caused by the reduction in the rate of movement of inert and/or formation of large clusters particle, which may lead to the collapse process and loss of raw material.

Processes in spouted bed still lack a control strategy that guarantees closed loop operating under a condition of stable spouting. This is due mainly to the difficulty of obtaining a reliable variable, with fast response and easy to acquire in real time during the unit operations in this equipment.

Spectral analysis of the pressure fluctuation signals has been reported as a way to identify and monitor the fluid dynamic regimes in slot-rectangular spouted bed (Taranto, 1996), conical-cylindrical spouted bed (Silva, 1998; Xu *et al*., 2004; Lourenço, 2006; Lopes *et al*., 2009), fluidized bed (Silva *et al*., 2011) and vibrofluidized bed (Nunes *et al.,* 2011), although, it has not been used as an objective way to control or monitory process in a spouted bed to date reported.

In this context, this work aimed to study and evaluate the behaviour of pressure fluctuation signals and their power spectra in spouted bed processes. Spectral changes caused by mechanics and kinetics particles changes were obtained from the gas velocity decrease and compared with visual observations to identify the different phenomena that occur in each fluid dynamic regime. Three variables were monitored within the range of 5 – 20 Hz, spectral dominant frequency and spectral dominant amplitude of the

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pressure fluctuations signals and standard deviation of pressure fluctuation signals. Glass beads were used as inert particles in the spouted bed and air as the spouting gas.

2. Materials and methods

2.1 Materials

As inert particle, a load of 1 kg of glass beads (Potters, Brazil) was used, which represents a height of fixed bed 0.1 m. The physical characteristics of the particles are presented in Table 1.

Table 1: Inert particles characteristics

Particles	Average diameter	Density	Bulk density	Bed Porosity
Glass beads	0.0026 m	2500 kg/m^3	1630 kg/m^3	0.35

2.2 Experimental section

The equipment consisted of a Plexiglas conical-cylindrical spouted bed with include angle of 60 ° and inlet air diameter of 0.03 m, column diameter of 0.2 m with 0.5 m in height. Pressure data from the spouted bed were collected by a differential transmitter (Cole Parmer®, 68014-18, EUA) connected to a data acquisition system (National Instruments™, NIcDAQ 9172, Finland) and computer.

2.3 Method section

We used pressure fluctuation data acquired from the gradual air flow rate decreases (0,0016 m/s) accompanied by visual observations that describe the movement change of the particles. The pressure fluctuation signal was processed by a digital filter IIR Butterworth lowpass type, order 25 and 20 Hz cutoff frequency, normalized and applied the Fourier transform algorithm using the FFT (Fast Fourier Transform). The calculation of the FFT and the power spectrum is performed by FFT Power Spectrum VI in software Labwiew™ 8.6. The sampling rate was 400 Hz and the number of points 2048 (2^{11}), which ensure a good spectrum resolution. The temperature of inlet air was maintained in 343 K.

3. Results

3.1 Pressure fluctuations signals

The normalized pressure fluctuations signals acquired on different fluid-dynamics regimes are shown in Figure 1.

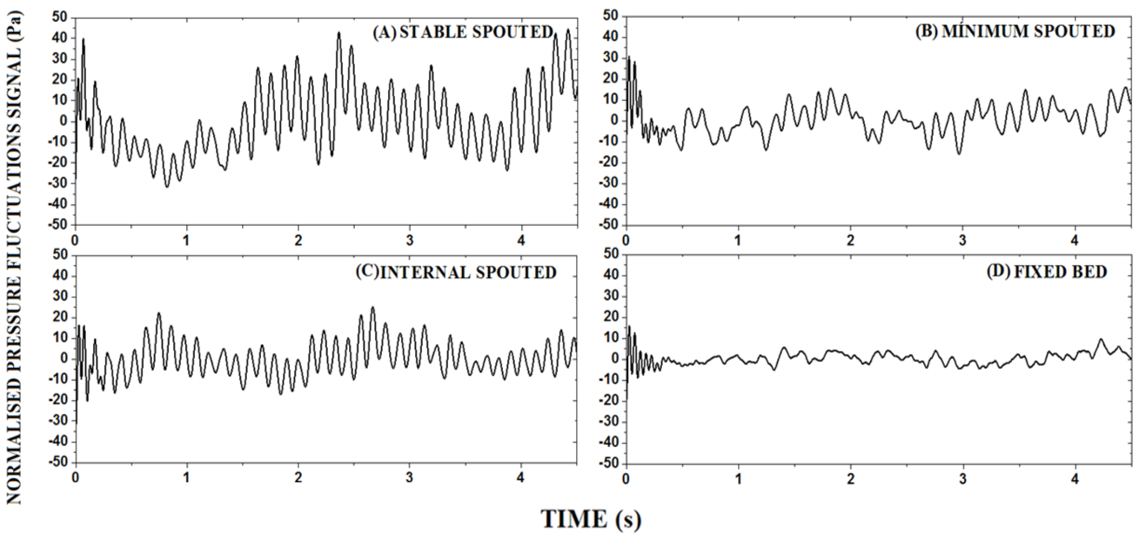

Figure 1: Pressure Fluctuations signals on different regimes. (A) Stable spouted U_{ar} = 0,37 m/s; (B) minimum spouted U_{ar} = 0,32 m/s; (C) internal spouted U_{ar} = 0,26 m/s; (D) fixed bed U_{ar} = 0,10 m/s

Focusing in Figure 1, it can be seen differences on amplitude, frequency and shape pressure fluctuations signals. Similar results are related by Taranto (1996), Silva (1998), Xu *et al.* (2004), Lourenço (2006) and Lopes *et al.* (2009), for different particle and spouted bed configurations.

Pressure fluctuations signals from stable spouted regime (Figure 1 (A)) and internal spouted (Figure 1 (C)) have sinusoidal shape when compared with a minimum spouted and fixed bed. This behaviour is attributed by the vigorous and cyclic movement of particles above the spouted and internal spouting regions, causing periodic oscillations in pressure drop.

When the air velocity approaches the minimum spouting velocity (Figure 1 (B)), we visually observed changes in motion of particles, the fountain oscillation and reduction of movement of the particles become slightly randomly. These changes result in non-periodic oscillation behaviour of the pressure drop, reflecting on irregular pressure fluctuation signals. The irregular pressure fluctuations are a feature of the dynamic instability.

In fixed bed regime (Figure 1 (D)), the amplitude of the oscillations of pressure drop is close to zero, due to the fact that air percolates through of particles without moving them, therefore, variations in pressure drop are not pronounced.

Although different dynamic regimes in the bed generated different pressure fluctuations signals, as discussed by Taranto (1996) and Silva (1998), this parameter does not prove to be an objective method for identification fluid-dynamic regimes, given the current state of technology available.

However, by Fourier transform of the pressure fluctuation signal it becomes possible to distinguish more clearly different dynamic regimes. Using a power spectrum in the frequency domain, the signal characteristics (frequency content) correspond to physical changes on global movement in the bed.

3.2 Spectral analysis

Figure 2 illustrates the power spectra generated from the Fourier transform of the pressure fluctuation signals shown in Figure 1, when the air velocity was reduced.

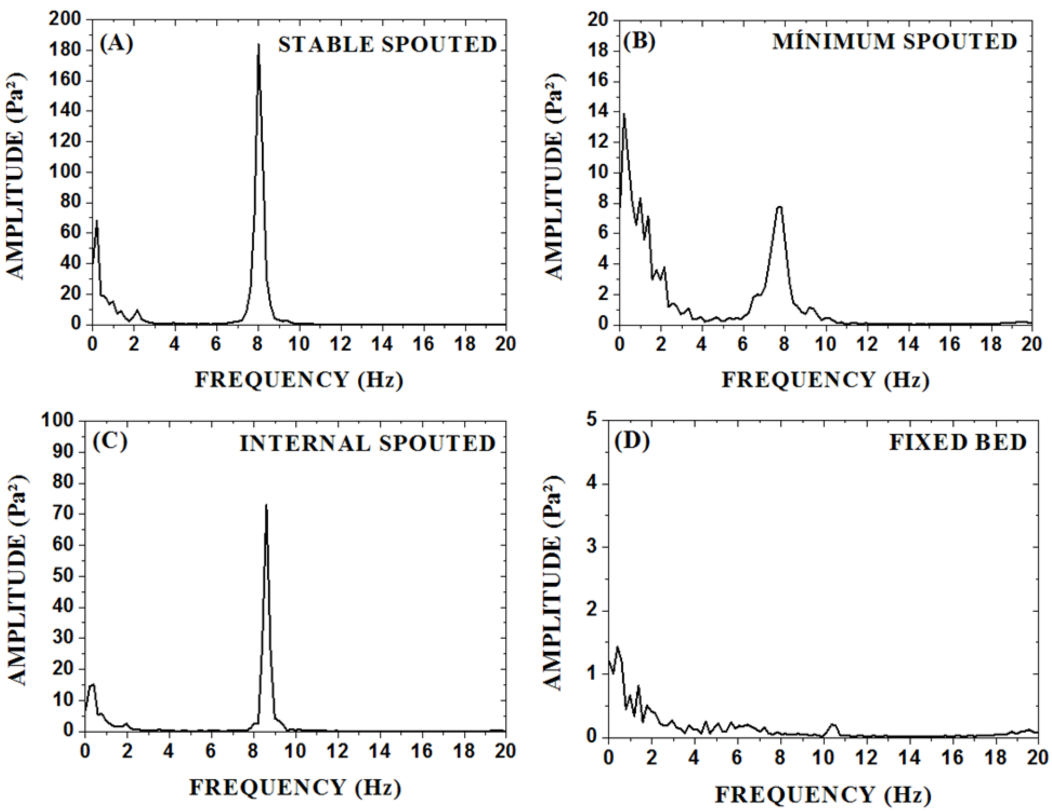

Figure 2: Power Spectrum. (A) Stable spouted U_{ar} = 0.37 m/s; (B) minimum spouted U_{ar} = 0.32 m/s; (C) internal spouted U_{ar} = 0.26 m/s; (D) fixed bed U_{ar} = 0.10 m/s

Figure 2 (A) shows characteristic peaks of stable spouted dynamics. Dominant frequency is 8.2 Hz and amplitude is 180 Pa^2. However, during the process, frequency varies between 7 and 9 Hz and amplitudes between 10 Pa^2 to 1200 Pa^2, depending on air velocity, particle motion, and pressure drop in the bed.
When the air velocity was decreased to approach of minimum spouted velocity, the stable spout dynamics was compromised and occurred transition tendency by internal spout regime, which was governed by a frequency and amplitude peak drop, shows in Figure 2 (A) e (B).
The amplitude and frequency drop during the regimes transitions demonstrates that these variables have high capacity to monitor the initial instants of instability in dry bed, warning a stopping point of the process or increase the gas velocity to reinstall stable regime.
From Figure 2 (C) it could be seen that there is an increase in the amplitude and dominant frequency when the internal spout regime is established. This spectrum is similar to the stable spout regime.
The Figure 2 (D) shows that in the fixed bed regime, there are not peaks, almost noises in the frequency region of 0 – 2 Hz with very low amplitude, caused by the vibration when the air passes between the particles.

3.3 Monitored variables

At instants before the transition regime (stable to internal spout), the spectral amplitude is very low, and it protrudes frequency peaks in two regions of the spectrum, that present similar values of amplitude. The coexistence of the peaks can be seen in Figure 2 (B). The appearance of two peaks in different regions of the spectrum when the regime approaches the instability can become an obstacle for the development of a conventional (PID algorithm) control strategy. We discretized the spectra in two different regions to facilitate the recognition of spectral patterns in very adverse physical conditions, isolating only the spectral region of interest.
When monitored all spectrum, dominant peak characteristics of spouted regime (7 – 9 Hz) alternating in predominance with low frequency peaks (0 – 2 Hz) from natural noises of the process. Taranto (1996) showed that when the bed spouted would lose stability, the spectra showed a second peak at 1 – 2 Hz on the spectra region, and thus demonstrated that the presence of more than one dominant peak is an indication that the spouted regime is in an unstable state.
The processes carried out in spouted bed are based on stable spout dynamics to provide high rate of heat and mass transfer. In this study, the spectral characteristics of stable spout were studied in detail.
The peak detection was performed by dividing the power spectra into two distinct regions. The first region comprised the range of 0 to 5 Hz while the second spectrum ranges from 5 to 20 Hz. Due to the predominance of stable spout peak frequency in the region between 7 and 9 Hz, studies are relied only on the 2nd region of the power spectrum (5-20 Hz).
The three variables monitored in this study were the dominant frequency peak, amplitude dominant peak and standard deviation of pressure fluctuation signals.
Figures 3 (A) and (B) showed the frequency and amplitude of the dominant frequency peak, respectively, and Figure 3 (C) shows the standard deviation of pressure fluctuation signals, during the period of the air velocity decreases. The amplitude and frequency variables are extracted by a virtual instrument called Statistics Express VI, tool of the LabWIEW™ 8.6 software.
As pressure fluctuations signals vary randomly even in stable spouted bed conditions, the oscillations naturally presented by frequency and amplitude, named with the letter (a), showed in the Figures 3, may hinder monitoring regimes and the development of a conventional control strategy. However, we decreased the amplitude oscillations through the mathematical treatment carried out by average of the RMS power spectra and smoothing of the dominate peaks.
The monitored variables named with the letter (a – line black) were defined as the variables acquired directly from the power spectrum every 5.1 seconds, and presents high oscillations. On the other hand, the variables defined with the letter (b – line grey) were obtained from the variable (a) after mathematical treatment for the purpose of smoothing of data. The mathematical treatment applied was smoothing average of three data extracted from the RMS average of the power spectrum.
From the analysis of Figures 3 (A) and (B) it is possible to distinguish three dynamic regimes. These regions were confirmed by the visual observations, such as: spout, internal spout and fixed bed.
It could be shown that during the spouted regimes, the dominant frequency decreases with decreasing gas velocity until around 0.31 m/s. The dominant frequencies (b) ranging between 8.8 and 7.5 Hz showed a stable spouted bed. However, frequencies below 7.8 Hz are an indication that the instabilities can arise.
The dominant amplitude has analogous behavior to dominant frequency. The stable spout regime, had dominant peaks with amplitudes between 1200 Pa^2 and 50 Pa^2. Reducing the amplitude (b) below 50 Pa^2 indicates difficulty in stability of spouted regimes.

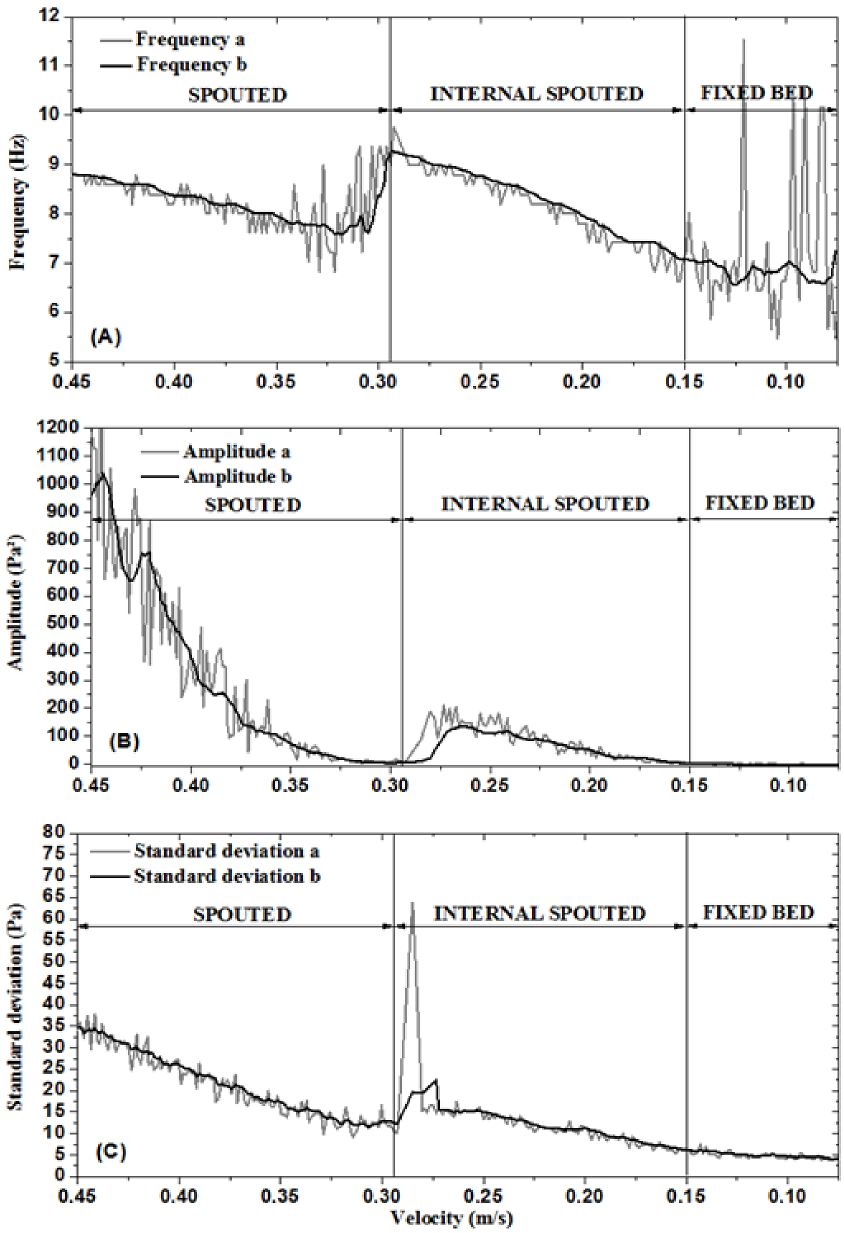

Figure 3: Monitored variables. (A) Dominant Frequency; (B) Dominant amplitude; (C) Standard deviation of pressure fluctuation signals.

Decreases in the air velocity during the stable spout regime lead to two consequences in the process, the reduction in pressure drop across the bed and the movement of particles, as might be observed visually. These physical alterations may be identified in the spectrum analysis through the frequency and amplitude of the dominant peak. The reduction in pressure drop causes a reduction of the spectral amplitude, while reducing the movement of the particles in the spouted causes a reduction in the dominant frequency.

When the gas velocity is insufficient to form the spout and the fluid-dynamic observed is internal spouted, the dominant frequency approaches of 9.5 Hz and amplitude recovery values close to 100 Pa^2, indicating an increase in the movement of the particles in the spout region and an increase of pressure drop.

The continuous decreases of the air velocity, then decreases the motion of the particles in the spout region (internal spout), reducing the dominant frequency to approximately 7.5 Hz, amplitude frequency and pressure drop to values near zero, indicating the initial moments of the bed collapse (fixed bed regime), although this point was difficult to define by visual observation.

By reducing the air velocity to reach the fixed bed, strong oscillations in dominant frequency (a – line black) over all spectral range studied (5-20 Hz) were observed, indicating that the characteristic peak of spout regime is nonexistent.

The study of standard deviation of pressure fluctuation signals also shows that this variable is able to monitor the dynamics of the spouted bed, and identify the fluid dynamic regimes. Figure 3 (C) shows the standard deviation of pressure fluctuation signals (a) and mathematical treatment standard deviation after smoothing average of three values (b).

Under the spout, the standard deviation decreases with decreasing the air velocity and particle motion, ranging from 35 Pa to 10 Pa. However, lower than 15 Pa the regime already presents low fountain under conditions close to change regime.

After the transition spout to internal spout occurs, an abrupt change in the value of the standard deviation is noticed. With continuous gas velocity decreasing, the variable gradually decreases from 16 Pa to 5 Pa with reduced internal cavity. When the standard deviation is less than 5 Pa the regime is already in a fixed bed. The observed results are consistent with those observed by Lourenço (2006).

The three variables studied in this work do not demonstrate lag time in the signal and showed good potential for application to control fluid-dynamics regimes in conical-cylindrical spouted bed dryers.

4. Conclusions

The study of fluid dynamic regimes in spouted bed from the spectral analysis of pressure fluctuation signals demonstrated that the three monitored variables exhibit well-defined bands for stable spouted regime, although the stable spouted and internal spouted regimes showed very similar spectral characteristics. The stable spouted is maintained while dominant frequency is greater than 7.8 Hz or dominant amplitude is greater than 50 Pa^2. Standard deviation is also a parameter for monitoring and should not be less than 15 Pa to keep the stable spouted regime. These variables have high ability to predict the initial moments of instability and can be used as a strategy to monitor and control in closed loop the fluid-dynamics conditions to maintain the stable regime.

Acknowledgements

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