DYNAMIC STUDY OF A GAS-SOLID CIRCULATING FLUIDIZED BED THROUGH PRESSURE FLUCTUATIONS ANALYSIS

Oscar Leonardo Cardenas-Fonseca
Yesid Javier Rueda-Ordóñez, yesid@fem.unicamp.br
Araí Augusta Bernárdez Pécora, arai@fem.unicamp.br
University of Campinas, School of Mechanical Engineering, R. Mendeleyev, 200, Zip Code 13083-860, Campinas, SP, Brazil

Emerson dos Reis, emersonr@cefetsp.br
Federal Institute of Education, Science and Technology of São Paulo – IFSP, Campus of São João da Boa Vista, Zip Code 13872-551, São João da Boa Vista, SP, Brazil

Abstract. *Pressure measurements have been used to characterize the dynamics behavior of fluidized beds since early researches in the area. Pressure fluctuations are due to gas and solid particles interactions within the bed, which characterizes the fluidization regime, but the origin of fluctuation is still not fully clear. Circulating fluidized bed (CFB) is an important technology with increasing application in processes like combustion, gasification and pyrolysis involving solids fuels as coal, biomass and municipal wastes. This paper presents an experimental study on the fluid dynamics of a circulating fluidized bed through pressure fluctuation analysis in order to identify the fluidization regime and operational conditions. A differential capacitive pressure sensor was installed in the riser (2.48 m height and 0.10 m internal diameter) of a CFB system to provide dynamics pressure signals measurements. The system was constructed using glass, acrylic and carbon steel allowing visual observation of the gas-solid flow. Tests were run using air and sand particles (207 µm mean diameter) as solid material. Measurements were conducted during a period of time and statistical analysis was applied to the collected data. Pressure fluctuations were analyzed in the time and frequency domains allowing the study of dynamic behavior of the circulating fluidized bed and estimation of transition velocities between fluidization regimes.*

Keywords: *Circulating fluidized bed, pressure fluctuation, signal analysis, fluidization regimes.*

1. INTRODUCTION

Fluidized beds are one of the most used systems in chemical industries due to their excellent fluid mixing, high heat and mass transfer rates and temperature uniformity. They are applied in many industrial processes including catalytic reactions, combustion and gasification of solid fuels, drying, adsorption, and catalyst regeneration (Kunii and Levenspiel, 1991).

Studies of pressure fluctuations in fluidized beds have been growing with the development of electronic devices such as pressure transducers, signal conditioners and data acquisition boards - DAQ. The analysis of dynamic pressure signals from fluidized beds became an essential tool for control and monitoring of the fluidization regime in industrial processes, since they reflect the properties of fluidized particles, the geometrical characteristics of the bed and the behavior of the bubbles (Chen *et al.*, 2004).

Pressure signals analysis has been applied in many studies (Wilkinson, 1995; Trnka *et al.*, 2000; Luckos *et al.*, 2007; Parise *et al.,* 2009; Bartels *et al.,* 2010), which involved the characterization of fluidization regimes and, therefore, prevention of a non-desired operational regime in the fluidized bed, detection of agglomeration and particle size changes, determination of minimum fluidization condition and characterization of transitions between regimes.

Yates and Simons (1994) presented an extensive review of experimental methods, probes and sensors in order to study gas-solids flows in fluidized suspension. They evaluated the application of different intrusive probes, comparing them with the most recent non-intrusive techniques including the tomographic ones. This work showed the special care to be taken on mechanical design of the probe, in order to avoid obstruction that can cause degradation of the pressure signal.

Pressure signals analysis through time-series methods can be classified into three categories: time domain methods, frequency domain methods and state space methods (Johnsson *et al.*, 2000; Van Ommen *et al.*, 2011).

Concerning the frequency domain methods, dominant frequencies of the pressure signal can be distinguished from Power Spectral Density – PDS data. The application of this method in fluidized bed studies is often cited in literature (Johnsson *et al.*, 2000; Parise *et al.,*2009;Van Ommen *et al.,* 2011). The method provides the knowledge of the dynamic properties of the fluidized bed, and allows the determination of the transition velocities between regimes of fluidization (Sasic *et al.,* 2007).

Van Ommen *et al.* (1999) studied the influence of the probe dimensions by analyzing the results of different methods (spectral analysis, statistical analysis and chaos analysis). They proposed a method to calculate the frequency response of the transducer-probe system in order to determine the most favorable dimensions to be used in experimental researches. Their results showed that probes up to 2.5 m in length and internal diameter ranging from 2 to 5 mm do not affect severely the quality of results. They justified their results as function of the frequency range studied that was up to about 20 Hz. However, the authors recommended the probe's length as short as possible.

Probes covered with wire mesh gauze (144 µm mesh diameter) made by tubes, of 4 mm internal diameter, were used by Bartels *et al.* (2010) for the tests in the cold bed lab-scale circulating fluidized bed (CFB). Measurement tubes were purged with nitrogen to avoid the blockage by particles for the tests of combustion and gasification. Their results showed that dimensions of the probes were successful and did not affect the quality of the measurements concerning the detection of gradual changes on particle size as well as early detection of agglomeration at room temperature tests. Meanwhile, concerning tests at high temperature, many of the measurement taps were blocked and were not suitable for the analysis due to agglomeration process.

Bi and Chen (2003) analyzed pressure fluctuations in a series of fluidized beds of different diameters (0.05, 0.1, 0.29, 0.60 and 1.56 m). They showed that the maximum amplitude and standard deviation of pressure fluctuations increased with the increment in the superficial gas velocity in bubbling fluidized beds, but they were insensitive to the variation of axial location inside the dense bed. They also showed that signal amplitude increased with static bed height in shallow beds but became almost independent of static bed height on deep columns.

Felipe (2004) identified and characterized different fluidization regimes through pressure fluctuations using various types of solid material. Their analysis was made in the frequency domain by applying the Fourier transform, and studying the effect of the measurement method (differential and absolute) in different pressure tap positions along the column. The author recommended not installing pressure sensors close to the air distributor due to the turbulent zone just above the air distributor as a result of air jets arising from each orifice; formation and coalescence of bubbles in this region. Moreover, Felipe considered the plenum as the best point for pressure signals measurements, since it offers equivalent results, concerning precision, when compared with other measurement points in the gas-solid flow above the gas distributor, with the additional advantage of avoiding possible obstructions of the pressure sensors by the particulate material.

Parise *et al.* (2009) analyzed pressure fluctuations of a gas-solid fluidized bed through spectral analysis. The authors proposed a methodology, based in pressure fluctuation analysis using Gaussian distribution, for detection of the minimum fluidization region in the fluidized beds. Their results showed that this methodology allows the determination of the defluidization condition in a bed containing small sand particles (d_p = 180 µm). Tests using larger particles (d_p = 460 µm) showed that such a condition could not be easily identified by the authors, due to the presence of larger bubbles at an operational condition close to the minimum fluidization.

In a circulating fluidized bed, transition velocities depend on the rate of particles circulation and pressure balance in the main loop. Accurate determination of the transition velocities between fluidization regimes is complex due to these associated factors. Previous works (Brereton and Grace, 1992; Chehbouni *et al.,* 1994; Bi and Grace, 1995; and Bai *et al.,* 1996) suggested the existence of different fluidization regimes along the riser of a CFB for the same operational condition. This behavior is observed in the fast fluidized regime, where a dense region in the bottom section (bubbling bed or turbulent bed regime) and a dilute region in the upper section (pneumatic transport regime) presents quite different characteristics. Therefore, only one transition velocity is not enough to describe the different regimes in fast fluidized beds.

The present work intends to contribute in the area of pressure fluctuations analysis in CFB systems through determination of the dominant frequencies and the range of characteristic frequencies for each fluidization regime in a circulating fluidized bed lab-scale system operating at room temperature.

2. MATERIAL AND METHODS

Tests were carried out in experimental circulating fluidized bed (CFB) system shown schematically in Fig. 1. The riser (0.1 m internal diameter, 2.5 m length) was built by sections of glass (borosilicate), acrylic and steel, allowing the visualization of the operational regime. The return column or downcomer is composed by two glass (borosilicate) sections (0.063 m internal diameter, 1.25 m length and 0.005 m wall thickness) connected by a steel section. A perforated plate (0.001 m orifice diameter, 0.008 m pitch) was used as gas distributor. Tests were conducted using industrial quartz sand as solid material (205 µm and 2628 $Kg.m^{-3}$ as mean Sauter diameter and particle density, respectively) and two bed heights (0.17 and 0.25 m) of the packed bed (loose packing). Air flow at room temperature was provided by the blower SO (36 KPa maximum pressure and 0.1 $m^3.s^{-1}$ maximum air flow). An orifice plate PO, built under specifications of ASME MFC-14M-2003, and a differential pressure transducer DP, allows the air flow rate determination before going to the gas distributor PD and riser L_R.

A Lapple cyclone C1 (0.12 m internal diameter) collects the entrained particles to the downcomer DC, where an L-valve 0.065 m internal diameter VL assures the return of these particles to the riser. The air flow to the L-valve was provided by a compressor and the air flow rate was measured by a rotameter.

The bed pressure fluctuations were measured in the plenum by a differential capacitive pressure sensor SMAR model LD301 ranging from 0 to 50 kPa, with DC loop current from 4 to 20 mA connected to the DAQ by using a 250 Ω resistor. A hose (0.1 m length and 0.005 m internal diameter) connects the measurement point to the transducer.

Additionally a slender material filter was used to avoid the obstruction of the pressure probe. Figure 2 shows the pressure measurement system.

Different fluidization regimes were reached inside the main riser, shown in Fig. 1, by increasing the superficial gas velocity from zero to 1.6 m/s. The characteristics of the flow for each regime were then visually observed.

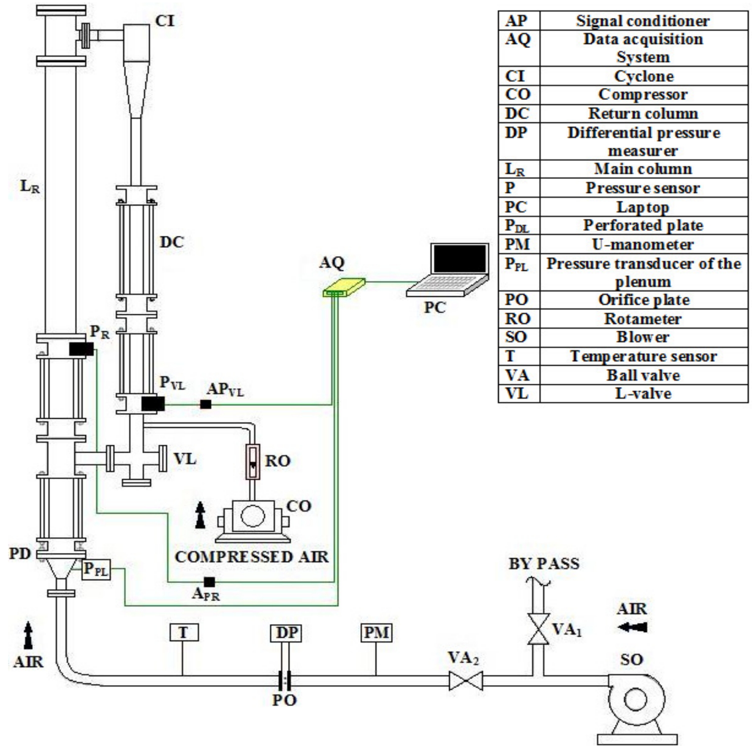

Figure 1. Schematic diagram of the experimental apparatus.

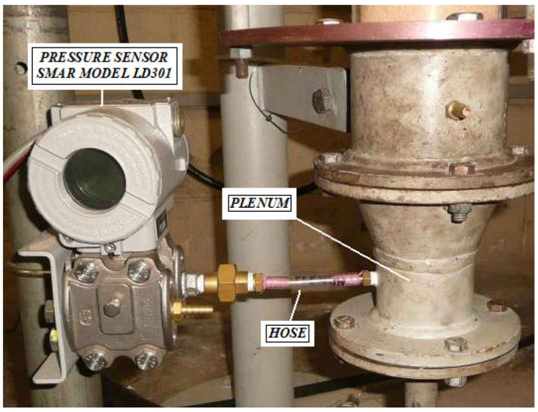

Figure 2. Pressure measurement system

Dynamic pressure signals were taken for 5 types of gas-solid contact chosen from visual observations. Superficial gas velocity at the main column (U_o) obtained from air flow rate data ($\dot{m}$) measured by the orifice plate are shown in Tab. 1 for each fluidization regime studied.

Table 1. Studied fluidization regimes and related superficial gas velocity (U_o) and air flow rate ($\dot{m}$).

Fluidization Regime	U_o (m.s^{-1})	$\dot{m}$ (kg.h^{-1})
Fixed bed	0.02	0.65
Bubbling bed	0.42	13.78
Slugging bed	0.65	22.10
Turbulent bed	0.88	30.81
Fast fluidized bed	1.58	61.81

The uncertainty of the pressure measurements in the differential capacitive pressure sensor SMAR was ± 1.03 Pa obtained by calibration using a U-type manometer and a multimeter, both previously calibrated and certified.

The dynamic pressure signals were acquired by a DAQ system model NI-USB 6255 from National Instruments™, 16 bits resolution and throughput of 1.25 MS/s. The LabView 8.6™ software was used for data acquisition and Matlab 7.0.1 software was used for signal processing.

The pressure sampling rate (f_s) in the tests was 200 S/s, determined by a series of preliminary tests in order to verify the highest frequency component (lower than 100 Hz by the Nyquist theorem), concerning a number of data sample (N_s) equal to 8192. This number of data points yields a resolution of 5 ms and the time resolution is good enough to sample a large number of the dynamical phenomena concerning engineering applications.

The time domain analysis allows the estimation of the signal behavior, however, a study involving the frequency domain is also necessary to improve the analysis from the acquired pressure signals.

The aim of the frequency domain analysis is to determine the power spectral density function - PSD, by using the fast Fourier transform algorithm - FFT, and, therefore, to obtain the dominant frequencies. From these results we can calculate the range of frequencies that represent frequencies representing around 70% of the amplitude of dominant frequency.

The pressure signal was modified by calculating its difference from the mean value ($\bar{P}$), obtaining $P_N(n)$ according to the Eq. (1) and Eq. (2), over which was applied the FFT to avoid the static component at 0 Hz in the PSD calculation.

$$P_N(n) = P(n) - \bar{P} \tag{1}$$

$$\bar{P} = \frac{1}{N}\sum_{n=1}^{N} P(n) \tag{2}$$

The standard deviation (σ) was calculated by the Eq. (3), in order to verify the reproducibility of the measurements.

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{n-1}^{N}(P(n) - \bar{P})^2} \tag{3}$$

The FFT was applied by the Matlab 7.0.1 software determining the Fourier transform $X(k)$ by Eq. (4).

$$X(k) = \sum_{n=0}^{N-1} W(n)\, P_N(n)\, e^{-j\left(\frac{2\pi}{T}\right)kn} \tag{4}$$

Where k = 0 to $N_s - 1$; $T = 1/f_s$; $j = \sqrt{-1}$ and $P_N(n)$ is the n_{th} pressure sample and $W(n)$ is the low-pass filter, necessary to reduce the leakage effect that occurs when additional frequency components appear.

The determination of the PSD from $X(k)$ was made by Eq. (5) using Pa^2/Hz^2 units, as function of the frequency component f given by Eq. (6).

$$PSD = \frac{2|X(k)|^2}{N_s} \tag{5}$$

$$f = k \,.\, f_s / N_s. \tag{6}$$

3. RESULTS AND DICUSSION

Figure 3 and 4 show the PSD obtained on tests at bed height (H_L) of 0.17m considering frequencies (f) from 0 to 10 Hz, which contain almost the whole spectral range, for each fluidization regime presented in Tab. 1. As can be seen, the pressure signals are affected by the superficial gas velocity (U_o) as the fluidization regimes. Figure 3 presents the PSD function for a superficial gas velocity inferior to minimum fluidization velocity (U_{mf}). At this condition the particles are stationary, characterizing the fixed bed regime. The air flow is low, showing almost zero pressure variations when comparing with the other regimes.

Increasing the superficial gas velocity, bubbles are observed in the fluidized bed, characterizing the bubbling fluidization bed. The PSD for the bubbling regime is shown in Fig. 4a, where a dominant frequency in 0.63 Hz and a range of frequencies from 0.3 to 3 Hz are observed. Big bubbles or slugs appear with an additional increase in the superficial gas velocity. The bubbles size increase and, when the diameters of the bubbles are about 60% of the bed diameter, the bubble is considered a slug, characterizing the slugging regime. Figure 4b presents the obtained PSD for the slugging regime, where the dominant components are from 0.30 to 1.50 Hz, and the whole frequency range is from 0 to 3 Hz.

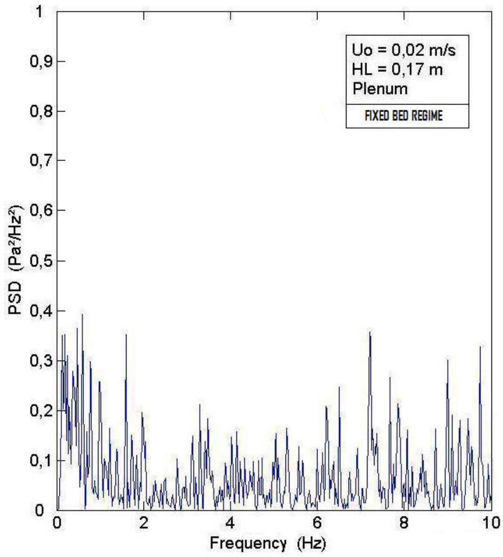

Figure 3. Power spectral density at the fixed bed operational regime, (U_o=0.02 m.s^{-1}).

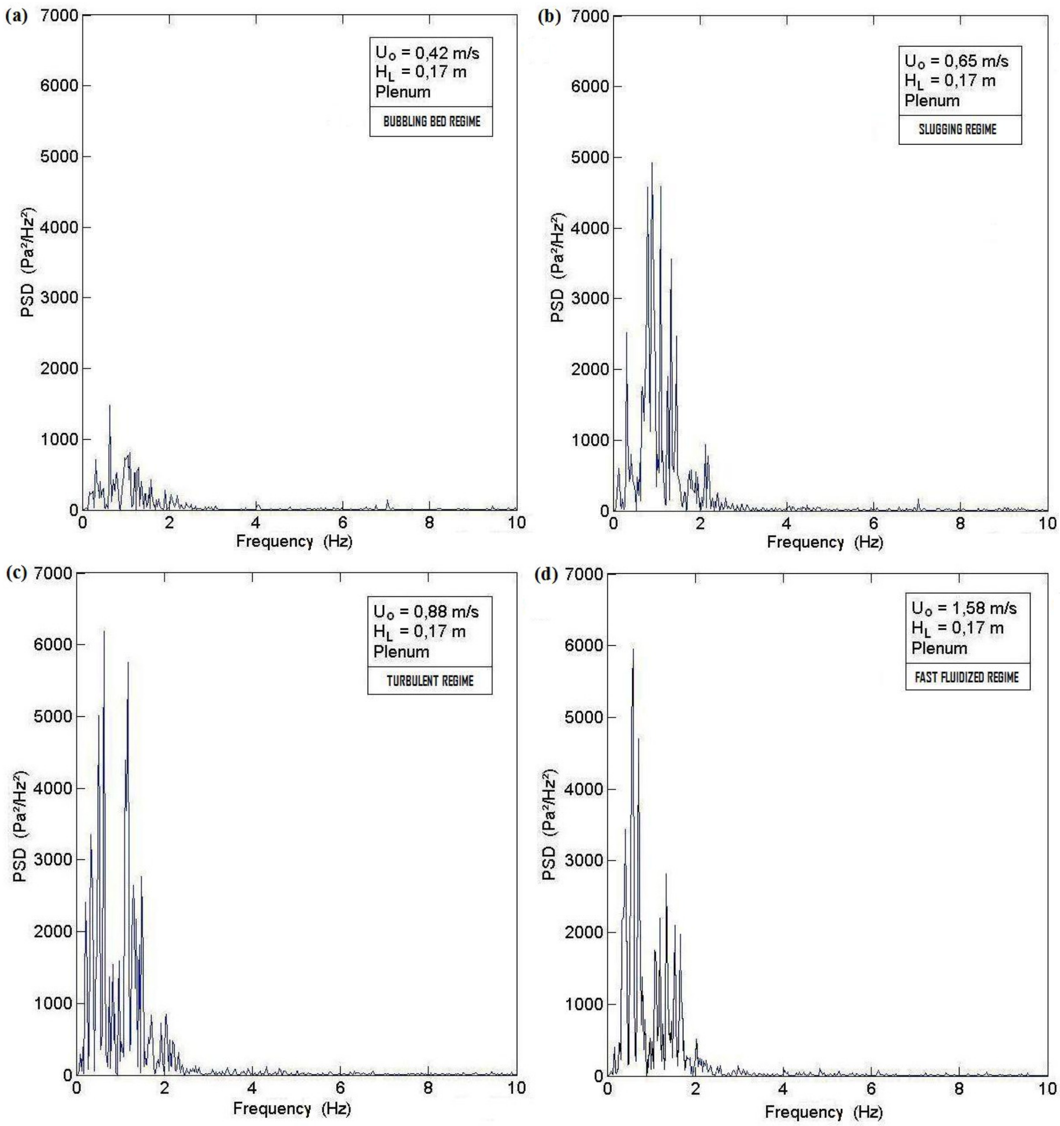

Figure 4. Power spectral density at (a) Bubbling bed regime, (U_o=0.42 m.s^{-1}); (b) Slugging regime, (U_o=0.65 m.s^{-1}); (c) Turbulent regime, (U_o=0.88 m.s^{-1}); (d) Fast fluidized bed regime, (U_o=1.58 m.s^{-1}).

Increasing even more the superficial gas velocity, bubbles of different diameters, ascending through the main column, are observed initializing the turbulent regime. In this condition particles are entrained from the bed resulting in a poor visualization of the bed surface. Figure 4c present the power spectral density of the turbulent regime, with a range of dominant frequencies from 0.34 to 1.17 Hz and a dominant frequency in 0.63 Hz. At this regime, another notorious frequency of 1.1 Hz was observed, being about 80% of the amplitude of the dominant frequency, this aspect does not allow the establishment of only one dominant frequency for the turbulent condition.

A small quantity of elutriated solid particles from the riser was observed under the turbulent regime. An additional increase in the superficial gas velocity lead to an increase in particles entrainment and more particles are elutriated from the main column. A Lapple cyclone collects the elutriated particles to the downcomer where an L-valve assures the return of these particles to the riser. These characteristics correspond to the regime of fast fluidized bed and Fig. 4d shows the obtained power spectral density. The fast fluidized operational regime presented a range of dominant frequencies from 0.41 to 1.34 Hz and a dominant frequency in 0.58 Hz.

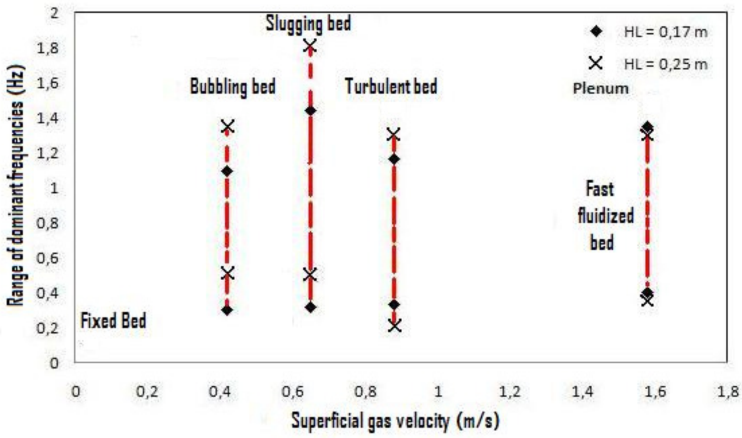

Figure 5. Comparison of the effect of superficial gas velocity in the range of dominant frequencies for two heights of loosely packed bed

Figure 5 shows that the effect of the increasing of the gas velocity in the range of dominant frequencies for the two bed heights (H_L) studied. An increase in the range of frequency was observed from bubbling bed to slugging bed regime. Meanwhile, it was observed a decrease in the range of dominant frequency range from slugging to turbulent bed and a very small variation from turbulent to fast fluidized operational regime. Figure 5 also show that bed height presented small influences on the range of dominant frequencies. Larger ranges were obtained for experiments using the highest bed height concerning operational regimes from bubbling to turbulent bed. There was not observed any influence of the bed height for the fast fluidized bed. These results agree with Dhodapkar and Klinsing (1993) and Fan *et al.*(1981) observations, who made tests using larger bed heights in comparison with this work allowing a clearer verification of bed height effect. Limitations of the experimental system did not allow bed heights upper to 0.25 m.

4. CONCLUSIONS

The fluidization regimes were characterized through analysis of spectral frequency density function based on pressure fluctuations in the main column of a CFB. Experimental results showed the spectral frequency density function on each fluidization regimes, allowing the characterization of gas-solid contact regimes through spectral analysis. The range of dominant frequencies was also determined for each operational regime allowing additional information to prediction of gas-solid dynamics from fixed bed up to fast fluidized bed. Bed height presented a small influence in the dominant frequency at the tested conditions concerning fluidization regimes from bubbling to turbulent fluidized bed.

5. ACKNOWLEDGEMENTS

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