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SPECTRAL ANALYSIS OF PRESSURE FLUCTUATIONS IN FLUIDIZED BEDS UNDER DIFFERENT REGIMES – A NUMERICAL STUDY

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Abstract. *Fluidized beds are used in various industrial processes in which a great contact between a fluid and a particulate solid phase is desired. In this paper, an Eulerian two-fluid-model was employed in the numerical simulation of the fluid dynamics of two fluidized bed reactors under different fluidization regimes - bubbling and fast fluidization - with Geldart-B particles. The objective of this work was to analyze the pressure fluctuations resulting from these simulations in order to get an insight of the main features of the fluid dynamics and to identify differences between different regimes concerning Power Spectral Density. The Power Spectral Density was obtained via Fourier transform of the pressure fluctuations at different positions in each reactor. The bubbling regime was characterized by peaks in frequencies of 1.5 and 2.2 Hz, while the fast fluidization regime was characterized by a peak at a very low frequency of 0.12 Hz, which is believed to be related to the frequency of falling clusters.*

Keywords: *Fluidized beds, gas-solids flows, spectral analysis, computational simulation, Fourier transform.*

1. INTRODUCTION

Fluidization is the process by which a liquid or gas flows through a particulate solid phase, keeping it under suspension, which causes the solid phase to have a fluid-like behavior. The interest in industrial applications of fluidized beds is mainly due to the large contact between the solid and gas phases during fluidization. (Kunii and Levenspiel, 1991). This technique is well known since the early nineties and became widely used since the 1970's in many processes of chemical and oil industry (Bittanti *et al.*, 2000). However, fluidized beds became more popular in the 1980’s and 1990’s along with the increased interest in power generation using solid fuels, due to the possibility of employing low rank coal and all sorts of biomass, and also because of the minimization of pollutant emissions (Baltazar *et al.*, 2009). Reliable mathematical models for fluidized beds are scarce yet owing to the complexity of the phenomena involved. The fundamental problem encountered in modeling hydrodynamics of a gas–solid fluidized bed is the motion of two phases where the interface is unknown and transient, and the interaction is understood only for a limited range of conditions (Gilbertson and Yates, 1996).

The flow regime in fluidized beds is a function of building and operational parameters. Figure 1 shows qualitatively the most common regimes in which Geldart-B particles (Geldart, 1973) may operate. In Fig. 1.(a) the fixed bed regime is illustrated. In this state the gas permeates the solid particles without moving them, and the porosity is minimum. When gas velocity is higher than the minimum fluidization velocity, the bed expands and the particles achieve the fluidized condition. For type-B particles, the formation of bubbles is immediate, and the regime is called bubbling (Fig. 1.(b)). When gas velocity is increased, the bubbles may turn into pistons (big bubbles which occupy more than 2/3 of the bed diameter), characterizing the plug flow regime, and still increasing gas velocity the flow achieves the turbulent regime (Fig. 1.(c)), in which bed surface is diffuse and difficult to distinguish. For gas velocities higher than the transport velocity, particles are carried out from the riser. This latter is called fast fluidization regime. If particles are re-circulated through the reactor, the process is called circulating fluidized bed (CFB) (Fig. 1. (d)). The fast fluidization regime is characterized by transients in high and low frequencies because the turbulent features of the flow and the formation of coherent structures such as clusters and pistons (Karppanen, 2000).

There are several mathematical models available for the multiphase flows which occur in fluidized beds. The numerical simulation of such systems using Computational Fluid Dynamics (CFD) must rely on models which are able to capture the desired flow features using the available computational resources. In this work, an Euler-granular mathematical model was chosen, due to its relative lightness and flexibility. In this model, the mass conservation and momentum balance equations are established separately for each phase. The coupling between phases is given by two-way momentum transfer model. The solid stresses, which differ much from the conventional fluid stresses, are modeled using the Kinetic Theory of Granular Flows of Lun *et al.* (1984). The version implemented in the code ANSYS/FLUENT 14.0 has been employed in the simulations presented herein. Further details on the numerical model may be found in (ANSYS Inc., 2011).

Experimentally, fluidized bed dynamics is usually studied through modeling and/or measuring porosity and pressure fluctuations in anywhere in the system. There is a discussion on how a calculated pressure can be compared to a measured signal in order to create a reliable representation of the fluid dynamics of the system. The type of information resulting from various ways of measuring the pressure in fluidized beds is also a point of divergence, as well as the use of absolute versus differential pressure probes (Sasic *et al.*, 2007).

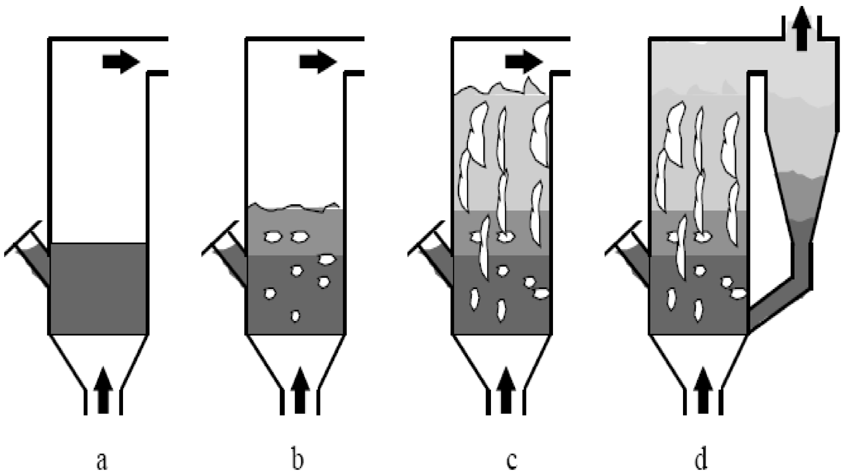

Figure 1. Fluidization regimes (a) Fixed, (b) Bubbling, (c) Turbulent and (d) Fast (circulating) (Karppanen, 2000).

A standard procedure for employing methods of time series analysis of pressure signals is also difficult to establish. The choice of a particular method must rely on what type of information that is seek. Sasic *et al.* (2007) point out, for example, that a local absolute pressure signal could give information on the flow as a whole, while from a differential pressure signal only local phenomena, happening between the two probes, could be inferred.

Analyses in time and frequency domains are the most common procedures for investigating the pressure signals recorded in fluidized beds. In the simple time-domain analysis, for instance, using standard deviation, the data requirements are not very strict. It is sufficient to have a pressure signal of 60 s, sampled at 20 Hz (Johnssonn *et al.*, 2000). More advanced methods of analysis in the frequency domain, e.g. a study of the probability density function (PDF) of pressure fluctuations requires considerably longer signals: more than 10 min is recommended, sampled at a frequency of 200 Hz or more. For nonparametric methods in the frequency domain, a sampling frequency of 20 Hz and a signal of typically 5 min would be enough, if one is interested only in the dynamics of large scales (bubbles). On the other hand, if finer structures are to be investigated, a significantly higher sampling frequency is needed, in general larger than 200 Hz (Sasic et al, 2007).

Pressure fluctuation data obtained from fluidized beds have been analyzed elsewhere by different methods, including standard deviation, PDFs, autocorrelation analysis and power spectral density (PSD) analysis. Standard deviation analysis gas been used to identify different regimes in fluidized beds, so as to determine minimum fluidization velocity and transition between regimes (Bi *et al.*, 1995; Zhang *et al.*, 1987 and references therein). The Fourier transform has been employed for obtaining the frequencies associated with a system via analysis of the PSD of the pressure signal, aiming to identify the relation between dominant frequencies and the physical phenomena occurring in fluidized beds (Iwasaki *et al.*, 1991; Deza and Battaglia, 2013).

The PSD analysis has also been used to validate similitude and scale-up rules (Brue and Brown, 2001; Nicastro and Glicksman, 1984). In this scope, Brown and Brue (2001) revised the sampling techniques commonly used for scaling beds, employing bubbling, turbulent and fast fluidization regimes. They recommend sampling times be at least 20 min and as long as 60 min to capture important low frequency dynamical information contained in pressure fluctuations. Furthermore, averaging at least 15 periodograms obtained from the data set should be employed. They also found that bubbling as well as CFBs behaved as multiple second-order dynamical systems and that unique peaks depending on the fluidization regime could be identified by PSD analysis.

Several researchers conducted experiments employing the PSD as the analysis tool. Johnsson *et al.* (2000) analyzed a CFB at different ambient conditions and fluidization regimes. Using PSD, they identified three regions: one macrostructure due to bubble flow and two other regions at high frequency due to finer structures. Van der Schaaf *et al.* (2002) determined bubble, gas slug, and cluster length scales from pressure fluctuation data measured in the bed and the plenum. Shou and Leu (2005) compared standard deviation with PSD and wavelet analysis to find the critical gas velocities for fluidization regime transition and found good agreement between the methods used to analyze the dynamics of the bed. Indrusiak *et al.* (2013) made a comparative analysis between Fourier and wavelet spectra of experimental pressure results for bubbling, slugging and turbulent fluidized beds, showing some intermittent characteristics of the phenomena. The bubbles presented themselves in the wavelet spectrum as a wake of low energy structures, with an inherent frequency of 2 Hz.

The pioneers to employ the PSD analysis to pressure fluctuations predicted by CFD were Wachem *et al.* (1999) and Benyahia *et al.* (2000). They both used two-dimensional Eulerian two-fluid-models (TFM) and reported reasonable agreement with experiments. Van Wachem *et al.* (1999) investigated PSD of CFD pressure fluctuations and void fractions of a bubbling fluidized bed (BFB). They found that the dominant frequency of the numerical pressure fluctuations were in agreement with experimental results. of these simulations. The power-law decay characteristics of the PSD of the pressure and voidage fluctuations also matched those observed in previous experimental work. Their main conclusion was that Eulerian simulations are able to correctly reproduce the dynamic characteristics of laboratory-scale fluidized beds, so Eulerian CFD simulations could used as scale-up tools.

Van der Lee *et al.* (2005) and Chandrasekaran *et al.* (2005) used TFM approach to investigate the behavior of linear low density polyethylene (LLDP) particles in a fluidized bed and compared their results with experimental data. They found that the employed TFMs (using ANSYS/FLUENT and MFIX) could not reproduce experimental results, mainly due the model inability to capture the effect of irregular sizes and shapes and the absence of data for critical solids parameters, such as angle of internal friction and coefficient of restitution.

Johansson *et al.* (2006) used PSD analysis to compare numerical and experimental data, and concluded that the TFM based on the Kinetic Theory of Granular Flows (KTGF) reproduced well the power spectra, and that the correct modeling of the air feeding system was crucial for predicting the overall dynamic behavior of the bed. This conclusion was also reported by Sasic *et al.* (2006) when they found that under certain conditions, a strong interaction between the inlet supply system and the gas–solid fluidized bed in the form of pressure waves was propagated.

Utikar and Ranade (2007) compared the PSD of experimental and numerical pressure fluctuations from a rectangular bed with a single jet operating in bubbling regime. The dominant frequency near the sparger was greater for the simulations than for experiments but compared well at higher locations in the bed, indicating the need of improving the values of solids properties in the KTGF.

Mansourpour *et al.* (2010) used a CFD-DEM approach to model a BFB bed of polyethylene particles. The PSD from the experimental pressure fluctuations showed a peak at 3 Hz, while simulation predicted a peak at 4 Hz, suggesting that numerical results overpredicted bubble sizes. A power-law fall-off, characteristic for fluidized bed dynamics was observed at high frequencies. This slope was equal to −4.3 and −3.7 for experiments and simulation, respectively.

Wang *et al.* (2011) concluded that pressure fluctuations originated above the distributor when a pulse of gas was injected in the bed. They also found that the amplitude of pressure fluctuation increased with the inlet velocity for BFBs, where two peaks were identified in the spectrum. Acosta-Iborra *et al.* (2011) found that using a 3D domain was necessary to model a BFB to obtain good predictions for power spectra and bubble behavior compared to the experiments. Using a two-dimensional TFM for a bubbling bed, Sun *et al.* (2001), found that the Syamlal and O'Brien drag model was the best choice in order to match numerical and experimental PSD results.

Deza and Battaglia (2013) performed a numerical study (TFM of MFIX) on the hydrodynamics of BFBs of sand and a binary mixture of cotton stalks and sand, comprising bubbling ($4U_{mf}$), slugging ($6U_{mf}$) and turbulent ($8U_{mf}$) regimes. They validated their results against the experimental ones of Zhang *et al.* (2008, 2009). They found that standard deviation of pressure drop was over predicted for inlet velocities greater than $4U_{mf}$ when using a 2D domain; therefore, the fluidized bed was appropriately modeled by using MUSCL discretization and the Ahmadi turbulence model for velocities equal to and greater than $6U_{mf}$, which corresponded to the peak of standard deviation of pressure drop. For all regimes, the system behaved as a second-order dynamic one. BFBs showed one peak while slugging and turbulent beds showed two distinct peaks. It was observed that the peak at low frequency increased in magnitude as the flow transitioned from slugging to turbulent fluidization regimes. The author concluded that CFD simulations of fluidized beds with the purpose of studying pressure fluctuations are a useful tool to obtain hydrodynamic information to determine the fluidization regime.

In this work, we use de PSD methodology to analyze pressure fluctuations resulting from the numerical simulation of two fluidized beds. The first one is a BFB of Geldart-B particles, based on the experimental work of Jung *et al.* (2005). The second one is the case 4 of NETL/PSRI Challenge Problem 3 (Shaddle *et al.*, 2010), which consists of a CFB using Geldart-B particles.

2. METHODOLOGY

First in this section the mathematical model in which numerical simulations are based and the PSD method employed to analyze these results are summarized. Then the two fluidized bed reactors investigated and their numerical modeling are described.

2.1 Mathematical equations

The mathematical model employed was the one implemented in the code ANSYS/FLUENT 14.0, which is based on an Eulerian two-fluid model (TFM) and on the he Kinetic Theory of Granular Flows (KTGF) of Lun *et al.* (1984). Further details on this model may be found in ANSYS/FLUENT theory guide for version 14.0 (ANSYS Inc., 2011). As the mass and momentum governing equations are solved for each phase, the continuity equation for any phase *i*, is given by:

$$\frac{\partial}{\partial t}(\varepsilon_i \rho_i) + \nabla \cdot (\varepsilon_i \rho_i \mathbf{u}_i) = 0 , \tag{1}$$

where ε_i, ρ_i and $\mathbf{u}_i$ are the volume fraction, density, and velocity for each phase i. The momentum equation for the of gas phase, g, is given by:

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g \mathbf{u}_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g \mathbf{u}_g \mathbf{u}_g\right) = -\varepsilon_g \nabla p_g + \nabla \cdot \boldsymbol{\tau}_g + \varepsilon_g \rho_g \mathbf{g} + \mathbf{K}_{gs}\left(\mathbf{u}_g - \mathbf{u}_s\right), \tag{2}$$

and for de solid phase, s, is given by:

$$\frac{\partial}{\partial t}\left(\varepsilon_s \rho_s \mathbf{u}_s\right) + \nabla \cdot \left(\varepsilon_s \rho_s \mathbf{u}_s \mathbf{u}_s\right) = -\varepsilon_s \nabla p_g - \nabla p_s + \nabla \cdot \boldsymbol{\tau}_s + \varepsilon_s \rho_s \mathbf{g} - \mathbf{K}_{gs}\left(\mathbf{u}_g - \mathbf{u}_s\right), \tag{3}$$

where p_i, g, $\boldsymbol{\tau}_i$ and $\mathbf{K}_{gs}$ are the fluid pressure, gravity, stress tensor for each phase i and gas-solid drag coefficient. The gas-solid drag coefficient is usually calculated using a gas-solid drag correlation. In this work, the one by Gidaspow (1992) was employed.

The gas phase is treated as an ideal gas with newtonian viscosity. As mentioned above, the solid phase stresses are modeled after the KTGF. In this case, an additional primal variable must be solved in order to close the problem. This variable is the granular temperature, Θ, which is the result of solid velocity fluctuations. The granular temperature is the basis for the modeling of the solid stress tensor and solid pressure. Its balance equation is given as:

$$\frac{3}{2}\left[\frac{\partial}{\partial t}\left(\rho_s \varepsilon_s \Theta_s\right) + \nabla\left(\rho_s \varepsilon_s \mathbf{u}_s \Theta_s\right)\right] = \left(-p_s \mathbf{I} + \boldsymbol{\tau}_s\right) : \nabla \mathbf{u}_s + \nabla \cdot \left(k_{\Theta s} \nabla \Theta_s\right) - \gamma_{\Theta gs} + \phi_{gs} , \tag{4}$$

where the first term on the right hand side is the generation of energy by the solid stress tensor, the second term is the diffusive term, in which $k_{\Theta s}$ is the granular temperature diffusion coefficient, the third term is the dissipation due collisions term, accounted by $\gamma_{\Theta s}$, and $\phi_{\gamma s}$ accounts for energy transfer between gas and solid phases. The definitions of these terms and details of the employed model may be found in FLUENT theory manual (ANSYS Inc., 2011).

2.2 PSD

The Power Spectral Density (PSD) is a method to analyze the energy content of a signal associated with to the frequencies of a physical phenomenon (Bendat and Piersol, 1971). The power spectral density function, S_{yy}, can be defined as the Fourier transform of the autocorrelation function R_{yy}, of a continuous time series, $y(t)$:

$$S_{yy}(f) = \int_{-\infty}^{+\infty} R_{yy}(\tau) exp^{(-i2\pi f\tau)}\, d\tau \tag{5}$$

$$R_{yy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{+T/2} y(t) y(t+\tau) dt \tag{6}$$

where f is the frequency, τ is a time shift, and T is the total length of the data set. For a finite time series the power spectrum can be computed as:
For the

$$G_{yy}(f) = \left|Y(f)\right|^2 \tag{7}$$

where $Y(f)$ are the coefficients of the Fourier transform of the time series $y(t)$.

For the spectral analysis, routines implemented in the code MATLAB were used.

The tool used to characterize the variability of a time series is the cross-correlation. It can also characterize the co-variation between two time series at two times, $t_1 = t$ e $t_2 = t + \tau$, where τ is the delay of the second over the first (Oliveira, 2010).

The cross correlation C analysis can be estimated for two signals A and B, where A and B are vectors length M (M>1), returns the length 2*M-1 cross-correlation sequence C. If A and B are of different length, the shortest one is zero-padded. C will be a row vector if A is a row vector and a column vector if A is a column vector.

Cross correlation provides an estimate of the correlation between two random (jointly stationary) sequences:

$$R_{xy}(m) = E\{x_{n+m}y_n^*\} = E\{x_n y_{n-m}^*\} \quad (8)$$

where x_n and y_n are jointly stationary random process, E { } is the expected value operator and - ∞ < n < ∞. The cross correlation must be estimate the sequence.

2.3 Case studies

2.3.1 Case 1 - Bubbling Fluidized Bed - Jung et al. (2005)

The first case studied was the BFB of Geldart-B particles from the experimental work by Jung *et al.* (2005). The gas phase was air at 298.15 K. The reactor consisted of a rectangular bed with dimensions L = 40 cm, W = 15.5 cm and t = 2.2 cm, as shown in Fig. 2. The simulation was carried out in three dimensions. For the gas phase, no-slip velocity boundary conditions were employed at the walls. For the solid phase, Johnson and Jackson (1987) partial slip boundary condition was used with no frictional contributions. In this study, the specularity coefficient, Φ, was 0.6, and the restitution coefficient at the wall was assumed to be equal to one for the particle phase. At the top wall, Neumann boundary conditions were applied to the gas-particle flow with a constant pressure of 101,325 N/m^2. At the distributor, the gas inlet velocity was kept constant and equal to 58.7 cm/s. The initial height occupied by solids, L_1, was equal to 20 cm, with solids volume fraction of 0.405. In this region the gas velocity was takes equal to the superficial velocity considering the inlet velocity by the distributor. The granular temperature was set to 10 cm^2/s^2. Operational parameters are summarized in Tab. 1, for ε_m the minimum bed voidage, u_0 is the superficial inlet gas velocity and p_{out} is the exit pressure. The total time of simulation was of 240 s. The first 52 s of simulation were not considered in the analysis to remove the initial transient. The time step employed was of 0.001 s. The pressure signal was taken at 6 positions along the riser: 0.75, 1.25, 19.75, 20.25, 38.75 and 39.25 cm. The acquisition frequency was equal to 1 kHz. A mesh consisting of 109,120 cells was employed guaranteeing that the size of the cell was at most of the order of ten particle diameters.

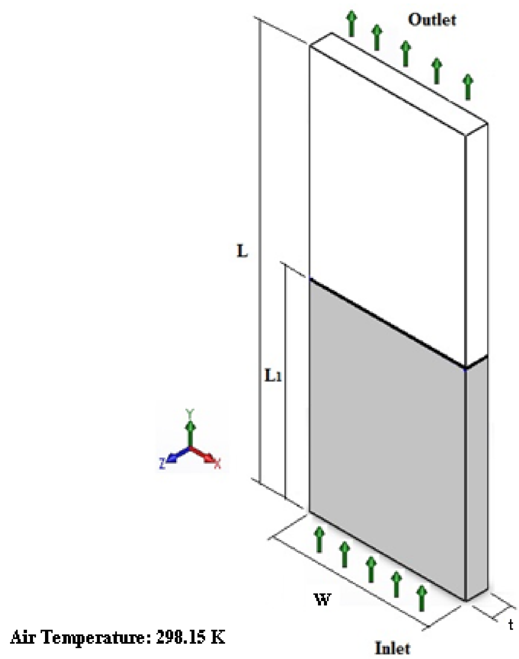

Figure 2. Problem domain considered in the numerical modeling of the BFB.

Table 1. Fluidization bed operational data.

d_p	ρ_s	ε_m	u_{mf}	u_0	p_{out}
530 μm	2500 kg/m^3	0.346	0.229 m/s	0.587 m/s	101,325 kPa

2.3.1 Case 2 - Circulating Fluidized Bed - Case 4 of NETL/PSRI Challenge Problem 3 (Shaddle et al., 2010)

This study was based on the experimental model presented in the Third NETL/PSRI Challenge of fluidized beds (Shaddle *et al.*, 2010, Breault, 2010 and Li *et al.*, 2012). It consisted of a riser operating in CFB regime with Geldard-B particles (ρ_s = 863,3 kg/m³, d_p = 802 μm). Table 2 summarizes the main operation parameters employed, where M_s is the solid circulation rate entering the riser, φ is the particle sphericity, ε_m is the minimum bed voidage, u_{mf} is the minimum fluidization velocity, u_0 is the superficial inlet gas velocity and p_{out} is the exit pressure. Figure 2 depicts the experimental facility and the two-dimensional geometry employed in the numerical model. A significant geometric adaptation was applied to the riser secondary inlet and outlet. In the experimental model, the inlet and outlet were unilateral. However, the use of a two-dimensional model with one-sided inlet and outlet tends to generate unrealistic asymmetric horizontal profiles (Chalermsinsuwan *et al.*, 2009). Thus, the riser secondary inlet and outlet were doubled in opposite and symmetrical side positions preserving the total cross sectional area of the real model. The scheme of the riser model geometry is shown in Figure 3. (b), where D is the riser diameter, L is the riser height, L_i is the size of each secondary inlet, L_o is the size of each outlet, .y_{si} is the secondary inlet midpoint vertical position and y_o is the outlet midpoint vertical position. For the real riser, the values for these measures were taken as D = 0.3048 m, L = 16.79 m, L_i = 0.115 m, L_o = 0.1015 m, .y_{si} = 0.43 m, y_o = 15.88 m. The initial condition was of only gas phase occupying the whole riser. The total time of simulation was of 170 s. The first 40 s of simulation were not considered in the analysis to remove the initial transient (time to achieve a constant value for the solids inventory inside the reactor). The time step employed was of 0.001 s. The pressure signal was taken at 10 positions along the riser: 1.04, 2.05, 4.09, 5.61, 7.34, 9.07, 10.34, 11.61, 13.02 and 14.94 m. The acquisition frequency was equal to 1 kHz. After performing a grid independence study, a grid consisting of 3360 control volumes was adopted.

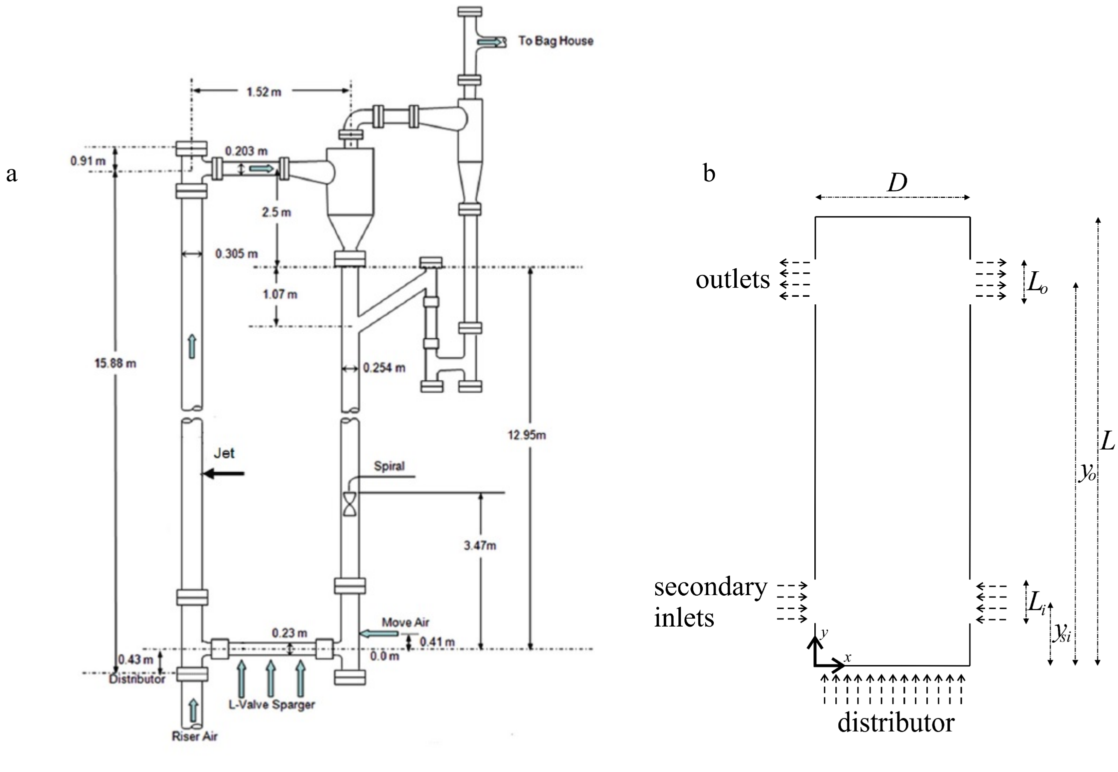

Figure 3. (a) Physical model for the CFB (Li *et al.*, 2012).
(b) Problem domain assumed in the numerical modeling of the CFB.

Table 2. Fluidization bed operational data.

d_p	ρ_s	φ	ε_m	u_{mf}	u_0	M_s	p_{out}
802 μm	863.3 kg/m³	0.95	0.346	0.13 m/s	7.58 m/s	7.03 kg/s	102 kPa

3. RESULTS

3.1 Case 1 – Bubbling Fluidized Bed - Jung *et al.* (2005)

In Fig. 4, solid volume fraction contours are depicted at 60, 140 and 240 s of simulation, showing the characteristics of a bubbling regime. In this condition, the superficial velocity is equal to 2.6 times the minimum fluidization velocity.

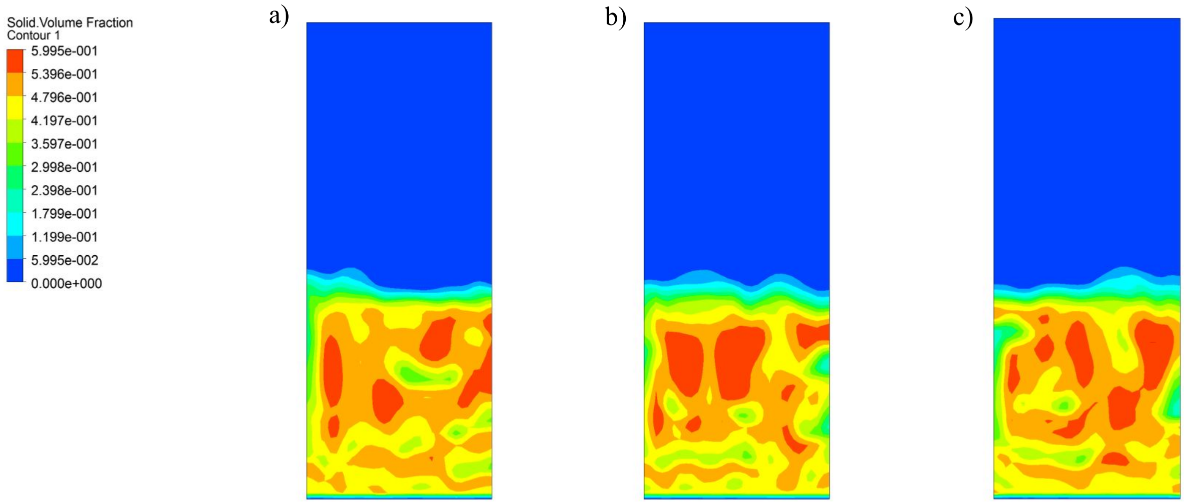

Figure 4. Solids volume fraction for the BFB at different time instants. a) 60 s. b) 140 s. c) 240 s.

In Fig. 5 the pressure fluctuation signal after 40 s of simulated time, measured at a position 0.1975 m above the distributor is shown. This data was used in the PSD analysis presented below. The mean value of the pressure signal was subtracted from the original signal in order to analyze a zero-mean signal. PSD analysis were performed using the whole data set and using its subsets consisting of half the period analyzed. The results regarding the whole set and its subsets were equivalent, which gave the confidence that the time interval studied was statistically representative.

Figure 6 shows the power spectrum obtained for this signal, obtained using 4096 FFT's, which was found to be the minimum number of FFT's to detect relevant frequency peaks. Two important frequency peaks may be observed. One is located at a frequency of approximately 1.5 Hz and the other, with higher amplitude, at a frequency of approximately 2.2 Hz. A peak at 2.2 Hz was expected and has been obtained in previous works regarding the simulation of BFBs (Jung *et al.*, 2005, Deza and Battaglia, 2013).

Figure 7 shows the cross correlation between two signals of pressure, collected at points located 0.75 cm (point 1) and 1.25 cm (point 2) above the distributor. The cross-correlation function resulted in a peak around 2.5 s, indicating that there is some phenomenon that takes place at point 1 and takes about 2.5 s to get to point two. This is probably related to the velocity in which bubbles travel within the bed.

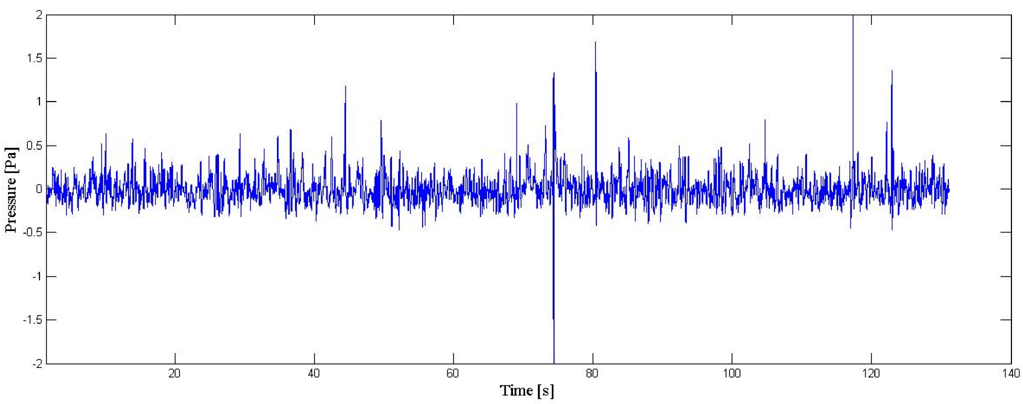

Figure 5. Pressure signal in the BFB.

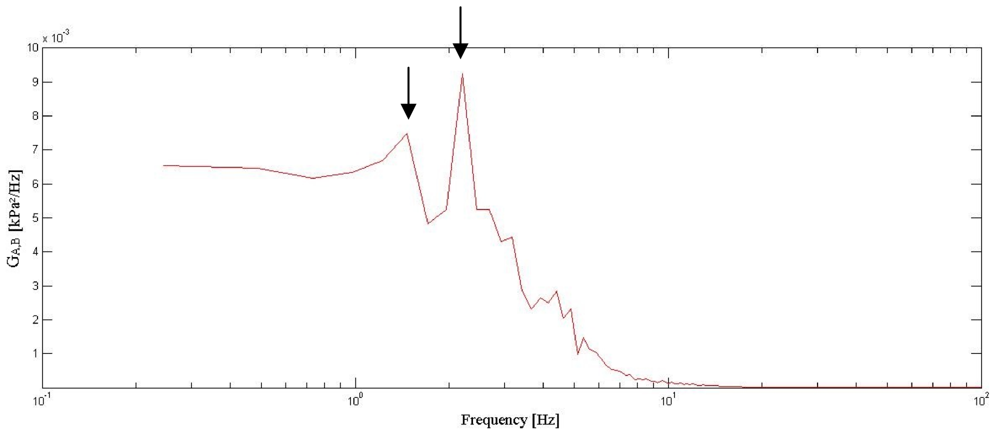

Figure 6. Spectral analysis for the BFB.

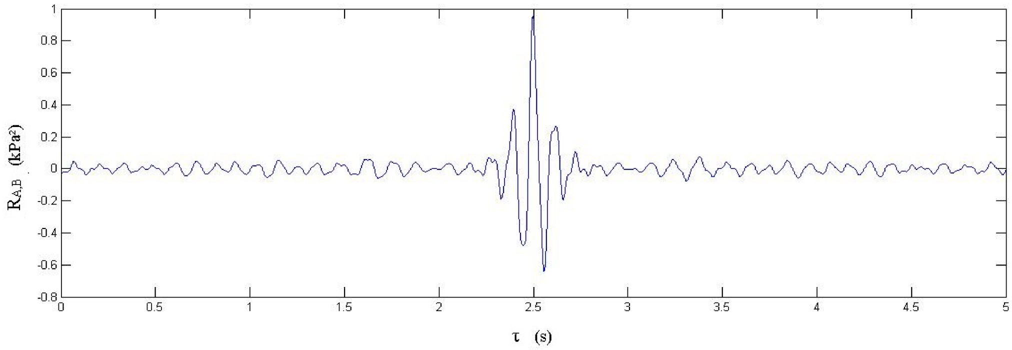

Figure 7. Cross-correlation for the BFB.

3.2 Case 1 - Circulating Fluidized Bed - Shaddle *et al.* (2010)

Some analysis regarding the flow characteristics obtained using the presented model were done. In Figs. (8)-(9), the results obtained for the time average solids velocity and solids mass rate profiles at a position 8.88 m above the distributor were compared with results previously obtained by Pedroso *et al.* (2013), and with experimental results available in Shaddle *et al.* (2010). In Fig. (10), the time average vertical pressure drop profile was also compared with results by Pedroso *et al.* (2013) using the code MFIX and the experimental results published by NETL and PSRI when disclosing the Third Challenge results (Shaddle *et al.*, 2010). The first step will be the validation of the numerical model for the flow inside the riser. An acceptable match between the results of the present work and experimental results may be observed in these figures, despite the present model underpredicts solids velocity in the center of the riser and overpredicts the solids mass rate. The pressure drop profile was also acceptable, considering the unrealistic exit conditions employed for the two-dimensional model.

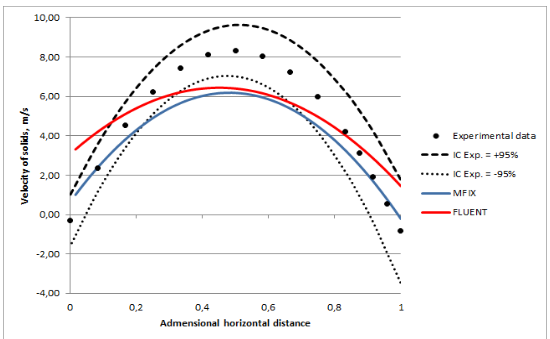

Figure 8. Solids velocity.

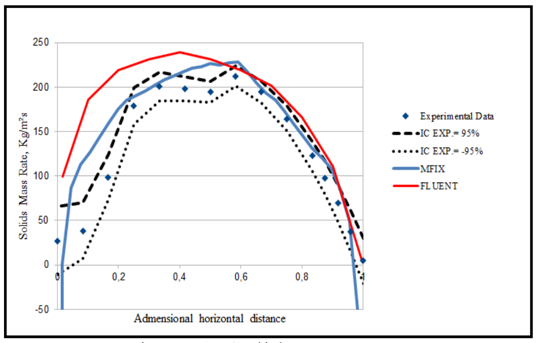

Figure 9. Solids mass rate.

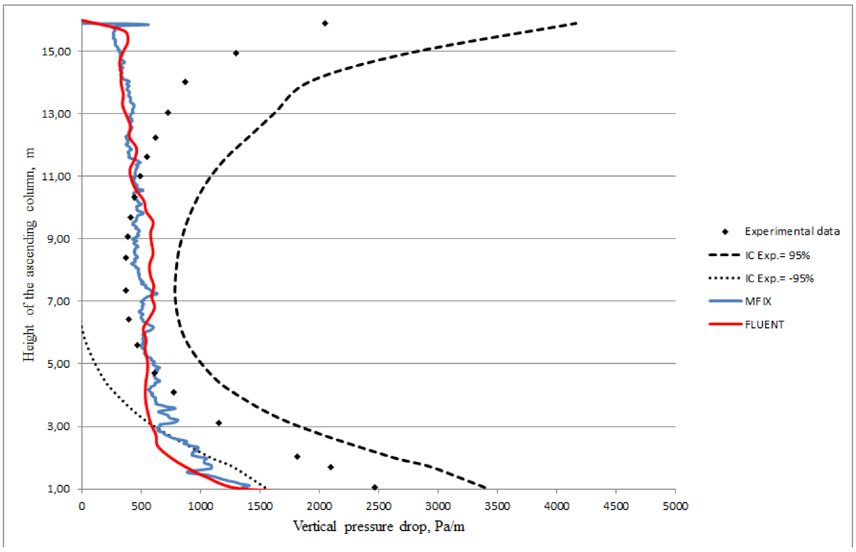

Figure 10. Pressure drop profile along the riser.

In Fig. 11 the pressure fluctuation signal after 40 s of simulated time, measured at a position 9.07 m above the distributor is shown. This data was used in the PSD analysis presented below. The mean value of the pressure signal was subtracted from the original signal in order to analyze a zero-mean signal. PSD analysis were performed using the whole data set and using its subsets consisting of half the period analyzed. The results regarding the whole set and its subsets were equivalent, which gave the confidence that the time interval studied was statistically representative.

Figure 12 shows the power spectrum obtained for this signal, obtained using 4096 FFT's, which was found to be the minimum number of FFT's to detect relevant frequency peaks. The pressure fluctuation signals were collected using a sampling frequency of 1 kHz over a time interval of 130 s after a steady value for the solids inventory inside the riser had been achieved. Analyzing the power spectrum of the CFB, there was a power surge at a very low frequency, about 0.12 Hz. This feature highlights the existence of clusters in bed, which are characterized as low frequency phenomena. Comparing the results of the power spectrum of the CFB with BFB it is observed that the power peak for the CFB occurs at a lower frequency than for the BFB.

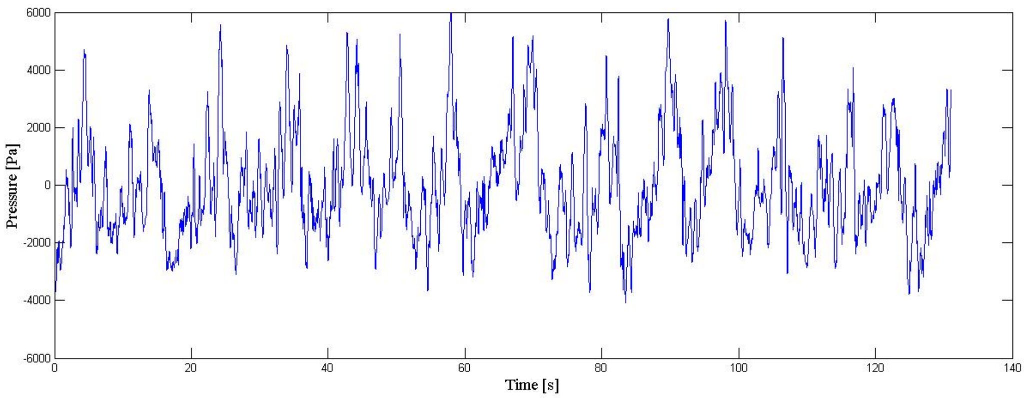

Figure 11. Pressure signal in the CFB.

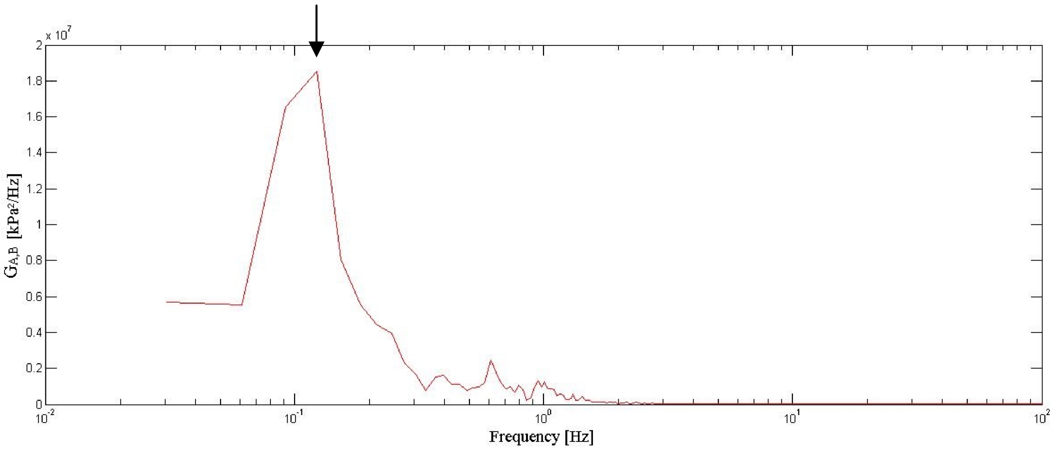

Figure 12. Spectral analysis of the CFB.

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