Chapter 12
Investigation of Turbulent Gas-Solid Flow Multi-scale Dynamics in a Circulating Fluidized Bed Riser

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Abstract Circulating Fluidized Bed (CFB) reactors have been extensively used for industrial applications such as mixing, drying, catalytic, and non-catalytic reactions. Due to the nonlinear and non-equilibrium gas-solid flow structures, the dynamic behaviors in a gas-solid multiphase flow remain far from being completely understood. In addition, considerable differences in the flow state occur under different operation conditions, resulting in different structures. These structures cause an impact on gas-solid momentum, mass, and heat transfer, affecting productivity. Pressure fluctuations are usually used to characterize dynamic behaviors of heterogeneous structures in fluidization. The signal of measured fluctuation contains the information about the multiscale flow characteristics and may also be associated with different phenomena. Identifying which scales of the flow are the most affected can help to reveal the dynamics of these different structures in gas-solid flow. The present work investigates pressure signals obtained through physical experiments at different experimental conditions in order to identify which scales were affected by the turbulent gas-solid flow. These signals were obtained in a CFB riser using glass beads particles, which were classified as group B of Geldart. Additionally, the gas velocity and mass flow were varied with the purpose of evaluating their influence over the turbulent scales. The obtained signals were investigated on the frequency and time-frequency domains. The power spectrum density (PSD) was applied to identify the dominant frequencies, as well the Wavelet transform was used as a mechanism to obtain the scales where its fluctuations were evaluated. The combination of such analyses resulted in the identification of the most affected scales, where it was observed

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that the mesoscales were attenuated with the addition of particles resulting in an increase in the fluctuation of the microscales.

Keywords CFB riser · Gas-solid flow · Turbulence modulation · Pressure signal · Wavelet transform

12.1 Introduction

Circulating Fluidized Bed (CFB) reactors are widely used in the petroleum, mineral, and energy industries. Several gas-solid flow phenomena present in this reactor are related to the turbulence of the fluid phase. When particles are inserted on the flow the turbulence is affected, this interaction can make turbulence completely govern the particles' behavior or the presence of particles can also influence the turbulence, which is known as turbulence modulation (Utzig et al. 2015). As a result of gas-solid interaction, several dissipative structures formation as clusters, particle segregation, and deposition of particles near to walls are observed. These structures are assigned to nonlinear and non-equilibrium interaction, which impacts gas-solid momentum, mass, and heat transfer, therefore, affecting CFB's productivity.

The dissipative behavior present in this multiphase flow shows a multiscale characteristic and a coupling of multi-sub-processes, scale-dependent behaviors, and the coupling between different mechanisms at different scales. There are three main approaches used to identify the scales: the first consists of tracking the movement of all individual particles, thus knowing the details of the particle-fluid interaction; the second involves analyzing the average of all parameters in a specific volume and the third approach involves analyzing the system in three basic scales. Those scales are the particle scale, cluster scale, and unit scale, which represent the micro, meso, and macro scales, respectively (Li 2000).

Recently, an increased interest in pressure signal fluctuations to characterize dynamic behaviors of heterogeneous structures has emerged (Verloop and Heertjes 1974; Kage et al. 1991; Musmarra et al. 1995; M'Chirgui et al. 1997; van der Schaaf et al. 1998; Bi 2007; Sasic et al. 2007). Pressure measurements are easy to obtain even under severe conditions, as seen in the industry, relatively cheaper, nonintrusive, and avoid distortion of the flow around the point of measurement. Despite this and even though the pressure fluctuations signal contains information about multiscale flow characteristics, the interpretation of pressure signals is not totally understood (van Ommen et al. 2011). Signals processes techniques are commonly used to obtain information about the gas-solid fluid dynamics. According to Johnsson et al. (2000) these methods include the time domain, frequency domain, time-frequency domain, and state space. Although there are extensive data available in the literature, the experimental data are rather controversial and there is no general agreement about which scales are most affected by the addition of particles in gas-solid flows.

Pressure fluctuation analysis has focused on the fluidized bed phenomena to characterize the flow regimes and transition velocities (Shou and Leu 2005), bubbling behavior (Wu et al. 2007), dynamic properties of clusters (Yang and Leu 2009) and investigation of multiscale structures dynamics (Chen et al. 2016). However, not too much attention has been paid to the scales' communication dynamics and the interaction effects between turbulence and particles.

This paper will focus on the experimental investigation of which scale is most affected by the addition of particles in a pilot-scale CFB riser. The experimental data was obtained through pressure transducers and were analyzed using standard deviation, Fast Fourier Transform (FFT), and Wavelet Transform. With this information, the homogeneity of signal, predominant frequencies, and the dynamic of scales were observed.

12.2 Mathematical Modeling

12.2.1 Statistic Analysis

According to van Ommen et al. (2011) most analysis methods involving standard deviation Eq. (1) in fluidized beds were applied in time domain analysis and used to determine the amplitude of the pressure signals. This application has often been used to identify a regime change, minimum fluidization velocity and to quantify the stability of different flow patterns. The standard deviation is defined mathematically as

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{1}$$

where x_i indicates the measured datum within the acquisition duration, and its mean value $\overline{x}$ was calculated using Eq. (2):

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

In the present paper, the standard deviation was used to observe the fluctuation of the signal by means of the original signal homogeneity in the time domain and the scales in time-frequency domain.

12.2.2 Frequency Domain

The Power spectral density (PSD) analysis estimated by the Fourier transform is a widely used tool in signal analysis. In this analysis, the time domain signal is decomposed in a set of sinusoids of different frequencies. The advantage of using this technique is to determine the characteristic frequencies and their amplitudes. In the turbulent gas-solid flow, the change of the dynamic behavior results in changes in power spectra, which results in a variation of the dominant frequency (Felipe and Rocha 2004). At the same time, when it is applied the temporal position of the information is lost, resulting in the knowledge of all the frequency components, but being impossible to know when they occur.

The discrete Fourier transform (DFT) used was deducted as Bendat and Piersol (1986). Starting from the Fourier Transform of a temporal function, Eq. (3):

$$X(f, T) = \int_0^T x(t)e^{-j2\pi ft}dt \tag{3}$$

Assuming that x(t) is sampled at N space points equally spaced at a distance of Δt, where Δt is selected to produce a sufficiently high Nyquist frequency. The time of sampling is tn = nΔt, but it is convenient to begin with n = 0, so:

$$x_n = x(n\Delta T)n = 0, 1, 2, \ldots, N-1 \tag{4}$$

For the discrete version, to an arbitrary f:

$$X(f, T) = \Delta t \sum_{n=0}^{N-1} x_n e^{-j2\pi fn\Delta t}. \tag{5}$$

The usual selection of discrete frequency values for X(f, T) is.

$$f_k = \frac{k}{T} = \frac{k}{N\Delta t}k = 0, 1, 2, \ldots, N-1. \tag{6}$$

At these frequencies, the transformed values give the Eq. (7), which is now a discrete Fourier transform (DFT):

$$X_k = \frac{X(f_k)}{\Delta t} = \sum_{n=0}^{N-1} x_n e^{-j\frac{2\pi kn}{N}}k = 0, 1, 2, \ldots, N-1 \tag{7}$$

which is only valid for k = N/2 since the Nyquist frequency occurs at this point. From the discrete Fourier transform (DFT), the Power Spectrum Density (PSD) function Eq. (8) is defined as

$$PSD(f) = \frac{2|X_k|^2}{t_2 - t_1}. \tag{8}$$

where the PSD function is the magnitude of the FFT square divided by the period t_1 and t_2 (Cong et al. 2013). The shape of the power spectrum is subjective and depends on the number of samples (frequency of acquisition).

12.2.3 Time and Frequency Domain

To examine the chaotic characteristics of gas-solid interaction present in pressure signals and visualize the flow scales, the wavelet analysis was used to decoupling original pressure signals into different scales. The wavelet analysis transforms a signal in the time domain into the time-frequency domain. Initially, the continuous wavelet transformation is defined as Eq. (9)

$$f(a,b) = \langle f, \psi_{a,b} \rangle = \frac{1}{|a|^{1/2}} \int f(t)\psi^*\left(\frac{t-b}{a}\right)dt. \tag{9}$$

where ψ is the mother function, $1/|a|^{1/2}$ is a normalization factor, a represent the dilation parameter responsible for the localization in the frequency domain, and b the translation parameter that allows for the localization on the time domain (Sasic et al. 2006). As a result of non-periodicity of the signal, the dilatation and translation parameters are discretized:

$$a = a_0^m, b = n_l b_0 a_0^m \tag{10}$$

Thus, the discrete wavelet transform expression is obtained:

$$f(m,n_l) = \langle f, \psi_{m,n_l} \rangle = \frac{1}{|a_0|^{1/2}} \int f(t)\psi^*\left(a_0^{-m}t - n_l b_0\right)dt. \tag{11}$$

In essence, the discrete wavelet transform (DWT) is based on high-pass and low-pass filters, which decompose the signal into a low-frequency component A known as an approximation and a high frequency component known as D, called the detail (Mallat 1989):

$$f(t) = \sum_{i=1}^{k} A_k + D_j. \tag{12}$$

The decomposed signal known as bands or levels was grouped based on frequency, where each information bands represent information about a different frequency of original signal. This frequency can be related to the flow scale (microscales, mesoscales, and macroscales) and their respective phenomena. In the present paper, the wavelet decomposition was performed using a software coded in MATLAB © using the Daubechies 8 as the mother function to provide a multiresolution analysis.

12.3 Methodology

The experiments were run on the Pilot Unit of Riser and Cyclones, which can be seen in Fig. 1. This system consists of a riser made of acrylic with 12 m high and a T outlet. The internal diameter of the riser is 100 mm. Two cyclones placed at the exit of the riser returned the entrained solid to a reservoir. The solid used in the experiments as fluidized particles was glass beads with a mean diameter of 91 μm and particle density of 2450 kg/m^3, which were classified as Geldart group B. Atmospheric air was used as gas phase, and the relative humidity varied between 60 to 80%; the mean temperature was 25 °C and the pressure was 1 atm.

The system was operated in different experimental conditions. The mean gas velocity varied between 7 m/s and 10 m/s to provide information about how the increase of turbulence affects the flow scales. In order to identify the influence of the solid phase, different mass flow ($\dot{m}_s$) was used 0 kg/m^{2}s, 9.09 kg/m^{2}s, 20.23 kg/m^{2}s, 7.67 kg/m^{2}s and 15.80 kg/m^{2}s. These mass flow conditions were chosen to check the clean flow behavior and how the system variated with the addition of particles and the increase of the particles concentration.

The impact of the particles on the flow scales and their dynamics was measured through the acquisition of pressure signals obtained in the middle of the riser at 6 m from the particles feed, where the flow is developed. The data were collected using a differential pressure transducer with an output signal of 0–5000 Pa. The transducers were connected to the measurement points by small polyethylene tubes with an internal diameter of 5 mm and a length of 40 cm. A data acquisition system composed of a National Instruments USB-6000 board connected to a computer was responsible for receiving the pressure signals and transforming them into a digital signal. The frequency response used was 1000 Hz to be obtained in agreement with the Nyquist minimum frequency. The data was collected in 30 min and the first 10 s was analyzed, which resulted in 10,000 samples for each operational condition. The software created on the platform LabVIEW 2015 assisted in data visualization and acquisition, as well as in the reactor control system.

After the data acquisition, the processing was carried out with the aid of the MATLAB® software. Thereafter the PSD is calculated, the mother Wavelet function and the high-pass and low-pass filters are applied to the chosen levels, generating images of the details and approximation signals. Finally, the program stores and saves the data.

12.4 Results and Discussion

12.4.1 Frequency Domain

The power spectral density obtained for the experiments was used to analyze how frequencies behave in the different operation conditions. Figures 2 and 3 present

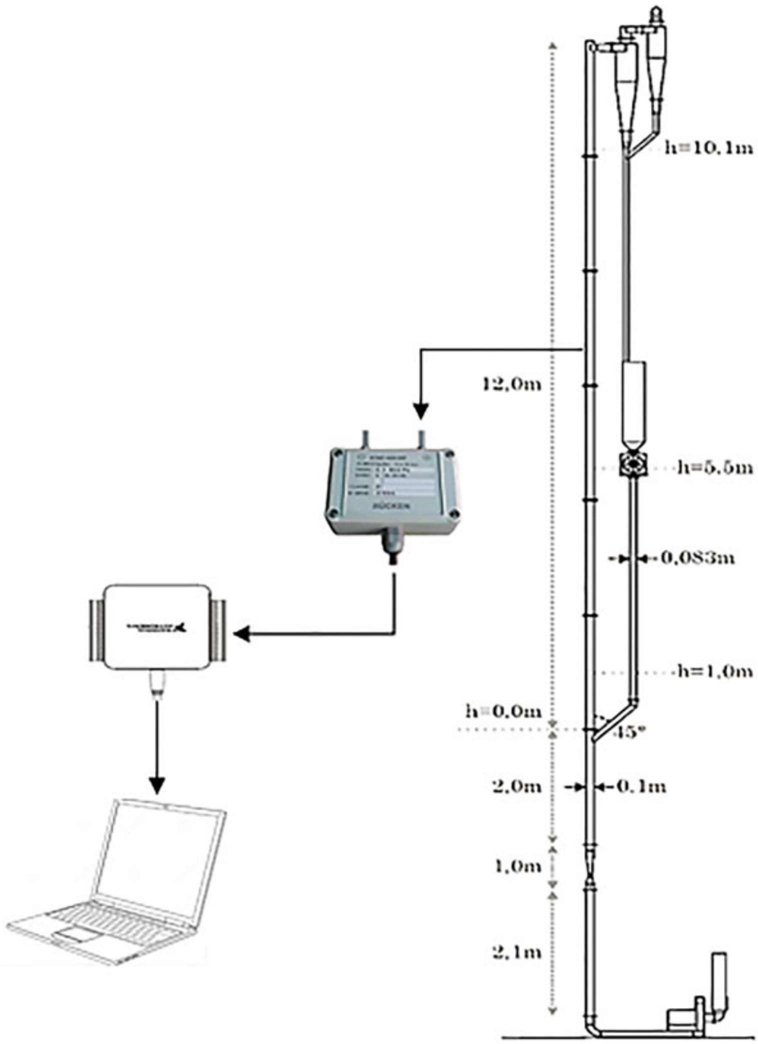

Fig. 1 Schematic of the experimental system: the pilot unit of riser and cyclones and the pressure acquisitions

the results for two gas phase velocities (v_g), 7 m/s and 10 m/s, respectively. It was observed in all cases several peaks across the spectrum with a frequency component of larger amplitude, almost always positioned at 30 Hz. According to Bi (2007), these highest intensity peaks are generally characterized as dominant frequencies, and these frequencies can correspond to different mechanisms.

When observing the predominant frequencies for the clean flow (Case A) at 7 m/s (Fig. 2), it is possible to see that the power peaks present in the high frequencies (70–300 Hz) were those that had the greatest variation, while the dominant frequency is

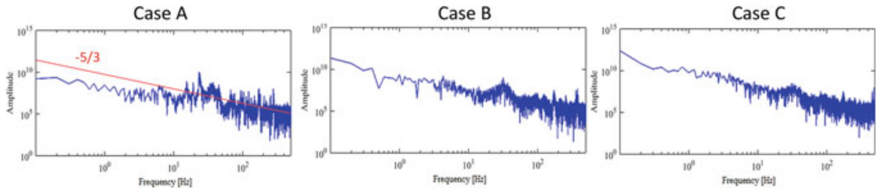

Fig. 2 Power spectral density, $v_g = 7\,\text{m/s}$: case A—clean flow; case B—$\dot{m}_s = 9.09\,\text{kg/m}^2\text{s}$; and case C—$\dot{m}_s = 20.23\,\text{kg/m}^2\text{s}$

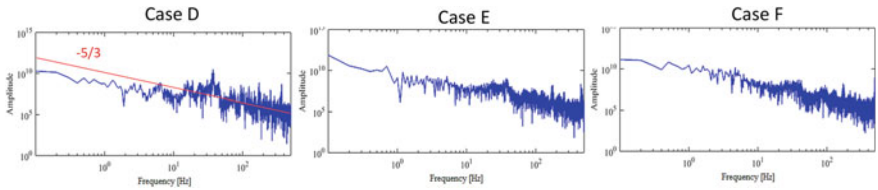

Fig. 3 Power spectral density, $v_g = 10\,\text{m/s}$: case D—clean flow; case E—$\dot{m}_s = 7.67\,\text{kg/m}^2\text{s}$; and case F—$\dot{m}_s = 15.80\,\text{kg/m}^2\text{s}$

25 Hz. When a flow of glass beads particles was fed (Case B), a low attenuation of the high frequencies amplitude is observed, the dominant peak moved to 30 Hz and a turbulent structure remains energized at 180 Hz. The increase of the solids flow (Case C), by its turn, results in stronger attenuation of the peaks around 100 Hz, except the one at 180 Hz. The increase in mean flow velocity to 10 m/s (Fig. 3) showed a shift to higher frequencies as a whole, even to the clean flow (Case D), where the dominant frequency changed to 35 Hz, this behavior was related to an increase in the energy of the system and consequently on turbulence. The solids mass flux is not the same compared to the lower flow velocity; however, there is a proximity between the ones of Cases B and E, C and F. Such comparison reveals that the energy intensity is nearly the same, although the frequency shifts an increase in peaks, the same characteristic of peaks attenuation with the addition of particles still was observed for all cases.

The results obtained show that the addition of solid particles impacts decreasing the power signals, which can be an indication of turbulence attenuation, while the increase in the gas phase velocity resulted in an elevation of the signal variation of the clean flow, as expected. On the other hand, the energized turbulent scales became the ones with higher frequency, those with smaller, more isotropic, and faster scales. The fact that the turbulent gas-solid flow is composed of multi-flow structures makes it difficult to determine the nature of the signal peaks. However, it was possible to observe that the 70–300 Hz frequencies were the most affected by particles.

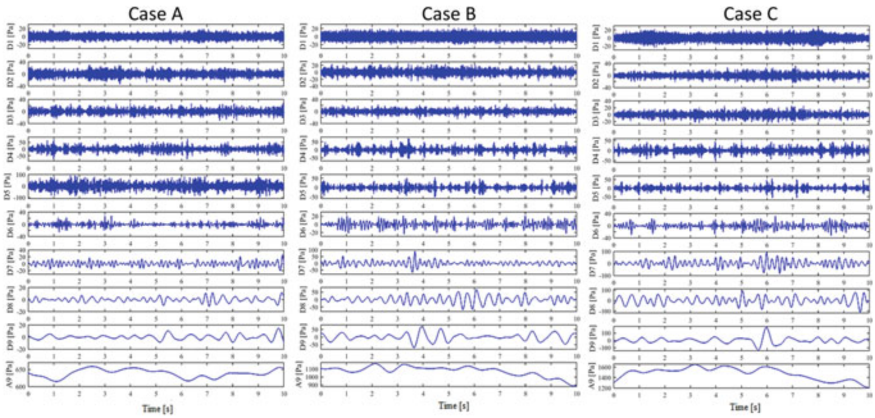

Fig. 4 Nine-level wavelet coefficients and one approximated coefficient of fluctuating pressure signal at the center of the riser ($v_g = 7\,\mathrm{m/s}$): case A—clean flow; case B—$\dot{m}_s = 9.09\,\mathrm{kg/m^2 s}$; and case C—$\dot{m}_s = 20.23\,\mathrm{kg/m^2 s}$

12.4.2 Time and Frequency Domain

In order to reveal features of the phase interactions in the gas-solid turbulent flow and verify which scales are most affected, the wavelet analysis was applied. The wall pressure fluctuations data collected was decomposed from wavelet levels 1 to 9, where each detail level represents a frequency range of the original signal. The 9 levels were the largest possible number of decompositions used for the 10 s time interval. Figures 4 and 5 provide an overview of all obtained fluctuation levels and are represented by the details D1, D2, …, D9 with the last approximation A9 at 7 m/s and 10 m/s, respectively. Both figures show the clean gas flow (Case A) and gas-solid flow cases with the increase of mass loadings (B and C).

Even though the results reflect the behavior of all scales, it is necessary to reveal the flow dynamics at different scales. As a result, the levels were separated to represent the flow scales based on the frequency. This division is illustrated in Table 1, where the phenomena of the main flow are presented based on each scale. As mentioned, the flow dynamics in fluidized beds systems is discussed at three levels of details. First, the microscale signals characterizing by phenomena with high frequency as gas turbulence, gas-solid and particle-particle interactions, were represented by components D1–D3. Then, the mesoscales that include frequency phenomena, localized at the medium range, as particles clusters and bubbles were characterized by components D4-D6. Lastly, the macroscales, which considers low-frequency phenomena, influenced by the effect of the fluidized bed unit geometry on the system behavior, have D7–D9 as representation components.

The homogeneity of the nine details was investigated using the standard deviation of each level and it is shown in Fig. 6. This statistical analysis makes it possible to

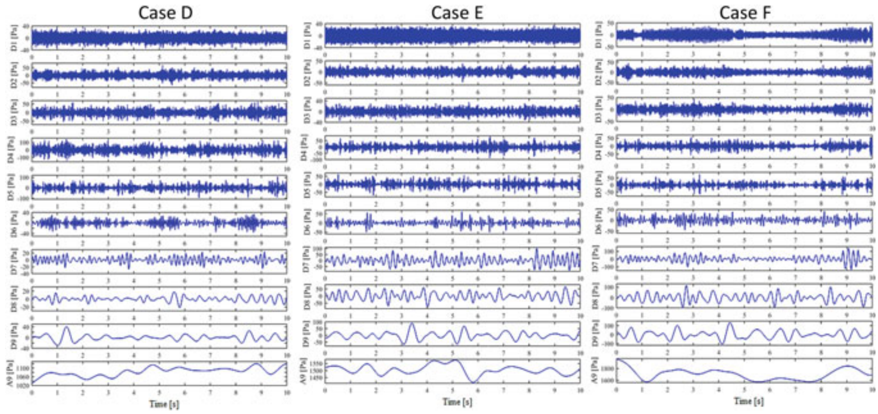

Fig. 5 Nine-level wavelet coefficients and one approximated coefficient of fluctuating pressure signal at the center of riser ($v_g = 10\,\text{m/s}$: case D—clean flow; case E—$\dot{m}_s = 7.67\,\text{kg/m}^2\text{s}$; and case F—$\dot{m}_s = 15.80\,\text{kg/m}^2\text{s}$

Table 1 Scale division, flow scales, and characteristics

Level j	Approximation A_j (Hz)	Detail D_j (Hz)	Flow scale	Flow characteristics
1	0–250	250–500	Microscale	Gas turbulence and particle-gas interaction
2	0–125	125–250		
3	0–62.5	62.5–125		
4	0–31.3	31.3–62.5	Mesoscale	Clusters
5	0–15.6	15.6–31.3		
6	0–7.81	7.81–15.6		
7	0–3.91	3.91–7.81	Macroscale	Unit scale phenomena
8	0–1.95	1.95–3.91		
9	0–0.977	0.977–1.95		

identify the levels with the greatest fluctuations by comparing these fluctuations between different experimental conditions.

For the clean flow (Cases A and D), the D5–D6 scales were the ones that achieved the greatest pressure fluctuation, thus it is estimated that the turbulent structures of the mesoscale were predominant in this flow. With the addition of particles with low solids mass fluxes (Cases B and E), the fluctuation of the mesoscales levels was attenuated, and the microscales D1–D3 were increased. As seen in Figs. 2 and 3, the energy intensity of the high frequency scales was attenuated, but the wavelet analysis shows that the fluctuation of these signals was increased with the solids flux. The pressure fluctuations of the turbulent flow scales between 125 and 150 Hz (D2) were increased 6 times from the $v_g = 10\,\text{m/s}$ clean flow to the dense flow ($\dot{m}_s = 15.80\,\text{kg/m}^2\text{s}$), while the 7.81–15.6 Hz scales were reduced 3 times in the same conditions. In the condition with the highest mass loadings (Cases C and F),

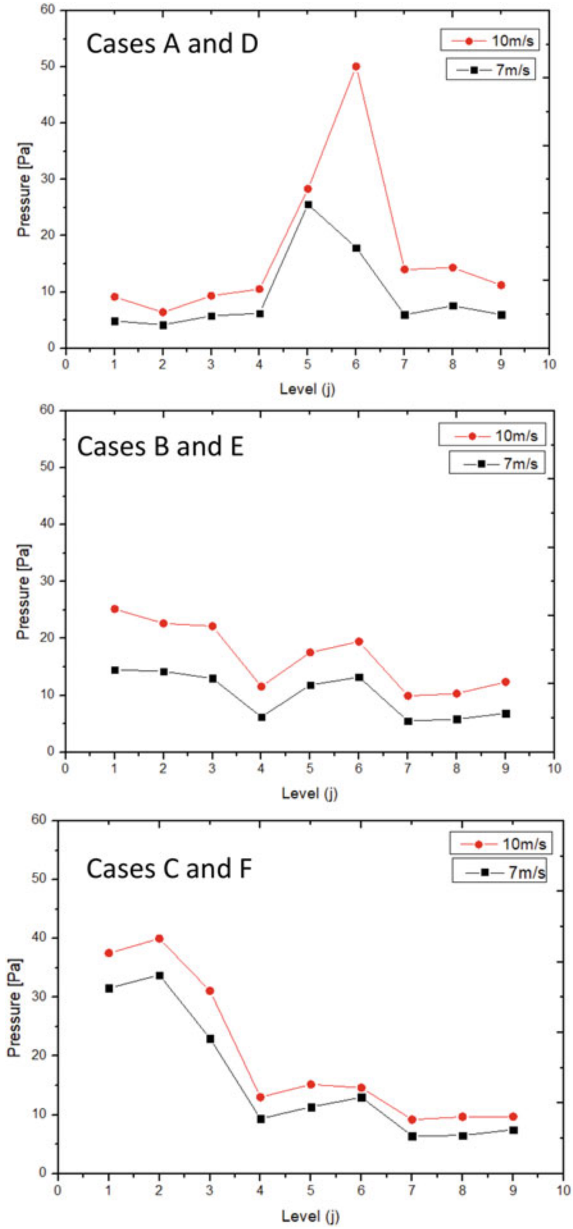

Fig. 6 Standard deviation of the pressure signals at each detail level: ($v_g = 7\,\mathrm{m/s}$): case A—clean flow; case B—$\dot{m}_s = 9.09\,\mathrm{kg/m^2s}$; and case C—$\dot{m}_s = 20.23\,\mathrm{kg/m^2s}$. . ($v_g = 10\,\mathrm{m/s}$): case D—clean flow; case E—$\dot{m}_s = 7.67\,\mathrm{kg/m^2s}$; and case F—$\dot{m}_s = 15.80\,\mathrm{kg/m^2s}$

the behavior observed in the Cases B and D was intensified at the microscales in a way much more relevant than at mesoscales. The increase of gas velocity resulted in the same behavior in all experiments, all scales pressure fluctuations were increased but they kept the same behavior. These results suggest that the addition of particles causes a dissipation of larger turbulent structures, at the same time two phenomena may be related to the increase in small scales. First, the particles split large structures assisting the dissipation process. Second, when the Kolmogorov length scales, which indicates that the smallest turbulent structures, are calculated to the clean flow as $\lambda_{K,7m/s} = 1.4 \times 10^{-4}\,\mathrm{m}$ and $\lambda_{K,10\,\mathrm{m/s}} = 1.1 \times 10^{-4}\,\mathrm{m}$, therefore, the smallest turbulent structures are of the same magnitude of particle size. Thus, the simple movement of particles can produce the smallest turbulent structures, or the particle-particle interaction can be responsible to increase the microscale fluctuation. These observations are similar to those obtained by Hussainov et al. (2000) and Utzig et al. (2015) for vertical flow.

Two objects of discussion were raised to explain the absence of structures in macroscales. The measurement point closer to the wall can influence the results, Gu et al. (2019) observed an action of the wall gradually appears and is restricted to medium-range fluctuations. Thus, this study did not consider the influence of the feeding and solids outlet. The observation time is another point of discussion, the short time of observation could be not enough to form structures with very low frequencies and large time and space scales.

12.5 Conclusions

Through the analysis of pressure signals wavelet transformation, the multiscale behavior contained in the turbulent gas-solid flow in the central region of a circulating fluidized bed riser was studied. The frequency and time-frequency domain were combined to observe the dominants frequencies and the most affected scales by particles. Relevant conclusions of this study were summarized as follows:

- The investigation of the predominant frequencies through the power spectral density, showed peaks along the entire frequency spectrum, where the greatest amplitude was observed at 20–30 Hz to the clean flows. With the addition of solids, these peaks were attenuated, such that the magnitude of this attenuation was directly related to the solids mass flow;
- The application of the Wavelet transform was performed for nine decomposition levels to the assessment of the most affected scales. The standard deviation of the detail levels revealed that at the single-phase flow the scales with the greatest fluctuation were as mesoscale classified. The addition of particles attenuated those scales, transferring energy to the microscales, which experienced greater fluctuations;

- The effect of the increase in gas phase velocity resulted in an increase in the flow scales intensity and the attenuation of mesoscales can be an indication of the influence of particles in the process of dissipating turbulent structures;
- The absence of well-defined macroscale structures was related to the short time of observation and the possible wall effect. Thus, for future work it is recommended to increase the investigation time and observe different radial measurement points as the effects of the entry and exit of solids. Measurements in these regions can supplement the information on the flow behavior;
- Lastly, the effects related to solid properties such as density and particle diameter used on the flow scales can add more information on the gas-solid interaction and turbulence modulation.

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