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Gas-Solid Turbulence Modulation: Wavelet MRA and Euler/Lagrange Simulations

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The presence of particles into turbulent gas flows can lead to modulation of the turbulence characteristics, i. e. visible in the pressure fluctuations. By means of computational fluid dynamics we can handle a variety of mathematical models to efficiently analyze the industrial applications, however, Reynolds Averaged solutions bring difficulties to detailed phase interaction investigation. Therefore, the goal of this study is to demonstrate the gas-solid interaction in Euler/Lagrange simulations and apply the wavelet Multi-Resolution Analysis (MRA) on wall pressure-time signals. Effects of particle properties and solids mass loading are evaluated. The wavelet MRA of the experimental wall-pressure fluctuations showed that the reduction of the variability is not monotonic from de highest time-scales to the lowest ones; the meso-scales (62.5 - 125 Hz) have considerable energy. Also, the presence of particles in the flow attenuates the pressure fluctuations, i.e. the clean flow has higher pressure fluctuation; the spatial micro-scales and meso-scales are the most affected scales of the energy spectrum in these operational conditions.

1. Introduction

Gas-solid flows have many important engineering applications, noticeably in fluidized bed combustion reactors (Miccio et al., 2014; Houshfar et al., 2013). Such cases disclose a number of intrinsic phenomena related to the fluid phase turbulence and once multiphase flows have peculiar characteristics, their behavior should be extensively evaluated. When particles are present, turbulence is modified and this is known as turbulence modulation. In previous studies we found that the RMS pressure component is attenuated by particles, i.e. clean turbulent flow has higher pressure fluctuations (Utzig, 2012). Since it is important to understand the modulation effects, special care must be taken regarding the mathematical model adopted through advanced experimental data.

The multi-resolution analysis of wavelet transformation on the pressure fluctuation signals is a powerful tool in the multiphase flow validation (van Ommen et al., 2011). Recently, wavelet MRA has been used to understand the multi-scale behavior of gas-particle flows, showing its ability to reveal phase interactions. An horizontal pipe system was investigated by Li (2002), who applied the wavelet MRA and found that larger gas-phase velocities results in larger pressure fluctuations in the higher frequencies, while lower gas-phase velocities, results in larger pressure fluctuations in the lower frequencies. The minimum pressure drop in a horizontal pneumatic conveying was studied also with wavelet transform, applied on particles by means high-speed PIV measurements (Zheng et al., 2012); the authors have found that lower frequencies dominate the fluctuating energy of axial particle velocity and contribute largely to the acceleration and fully-developed regimes.

Fluidized bed systems, where upward gas-solid flows occur, have been indirectly characterized via wavelet transform, applied to coherent structures identification in Eulerian-Eulerian simulations (Sun et al., 2012), flow patterns diagnostics by means pressure fluctuations and X-ray fluoroscopy measurements (Wu et al., 2007)

and particle clusters identification with optical fiber probes (Yang and Leu, 2009).
The purpose of this study is to demonstrate the gas-solid interaction in Euler/Lagrange simulations and investigate the scales of the turbulent gas-solid horizontal flow through wall pressure-time signals, by using the multi-resolution analysis of wavelet transformation. Knowing that few works has been done to validate the gas-solid computational fluid-dynamic models, these experiments are useful to better understand the simulations results.

2. Mathematical Models

2.1 Wavelet Multi-Resolution Analysis (MRA)

The wavelet transformation of a signal is done from a fine scale to a coarser scale by extracting information that describes the fine scale fluctuations and the coarser scale smoothness as:

$$\{\mathrm{D}_j\} = [\mathbf{G}]\{S_{j+1}\}, \tag{1}$$

$$\{\mathrm{S}_j\} = [\mathbf{H}]\{S_{j+1}\}, \tag{2}$$

where S represents mother-function coefficients, D represents wavelet coefficients, j is the wavelet level, and $\mathbf{H}$ and $\mathbf{G}$ are the convolution matrices based on the wavelet basis function (Li, 2002). The inverse discrete wavelet transform is similarly implemented via a recursive recombination of the smooth and detail information from the coarsest to finest wavelet level (scale):

$$\{S_{j+1}\} = [\mathbf{H}]^T\{S_j\} + [\mathbf{G}]^T\{D_j\}, \tag{3}$$

where $\mathbf{H}^T$ and $\mathbf{G}^T$ indicate the transpose of $\mathbf{H}$ and $\mathbf{G}$ matrices, respectively.
The original signal can be decomposed into many lower resolution components. Each level of decomposition contains information associated with a scale band. After decomposition, lowest-frequency component is called approximation and high-frequency ones are called details. The sum of all coefficients recovers the original signal.
Many different wavelet basis functions have been used in the investigations of gas-particle flow dynamics. The most common is the Daubechies family, since it emphasizes the smoothness of the analysed data, instead of the discontinuities ones. Therefore, in this study, Daubechies wavelet with an order of 8 (d8) has been chosen for the analysis of the experimental turbulent gas-solid flow pressure fluctuations. A Phyton code with a wavelet toolbox was used for signal processing.

2.2 Gas- and Solid-Phase Computational Fluid Dynamics Models

Gas-phase Model

The Navier-Stokes for a general, incompressible, steady-state flow can be written as:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0, \tag{4}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i + S_{p,Ui}. \tag{5}$$

The solution of the conservation equations for the momentum and turbulence is accomplished by the computational in-house code UNSCYFL3D. For further information on the numerical methods used in the code, the reference Souza et al. (2014) is recommended.
In all the simulations carried out in this work only the steady-state solution for fluid was sought. The second-order upwind scheme was employed for the advective term, whereas the centered differencing scheme was used for the diffusive terms of the momentum equations and turbulence model equations. The 2-layer k-epsilon model was employed, as it can handle well both the core flow and the near wall region.
The two-way coupling effects are computed by means an additional source term in the momentum equation. This term is modeled based on Newton's second and third laws:

$$S_{p,Ui} = -n\,\langle m_p\left(\frac{du_{pi}}{dt} - \left(1 - \frac{\rho}{\rho_p}\right)g_i\right)\rangle\,; \tag{6}$$

where *n* is the average number of real particles per unit volume in the control volume, m_p is the particle mass,

u_{pi} is the particle velocity, ρ_p is the particle material density, ρ is the fluid density and g_i is the gravity vector. The brackets denote mean values over all particle realizations in that particular control volume. Thus, for each computational particle crossing a control volume, one contribution is added to the source-term above.

Solid-phase Model

The dispersed phase is treated in a Lagrangian framework. The trajectory, linear momentum and angular momentum conservation equations for a rigid, spherical particle can be written, respectively, as:

$$\frac{dx_{pi}}{dt} = u_{pi}, \tag{7}$$

$$m_p \frac{du_{pi}}{dt} = m_p \frac{3\rho C_D}{4\rho_p d_p}\left(u_i - u_{pi}\right) + F_{si} + F_{ri} + \left(1 - \frac{\rho}{\rho_p}\right) m_p g_i, \tag{8}$$

$$I_p \frac{d\omega_{pi}}{dt} = T_i, \tag{9}$$

where d_p is the particle diameter, F_{si} is the shear-induced lift force on the particle i, F_{ri} is the rotation-induced lift force, $I_p = 0.1 m_p d_p^2$ is the moment of inertia for a sphere, ω_{pi} is the angular velocity of the particle i and the torque experienced by a rotating particle, T_i. The empirical correlation proposed by Schiller and Naumann (1935) is used to evaluate the drag coefficient, C_D, past each particle. The calculation of the shear-induced lift force is based on the analytical result of Saffman (1965) and extended for higher particle Reynolds numbers according to Mei (1992), and the rotation-induced lift force is based on Rubinow and Keller (1961).

Numerous experimental studies have shown evidence that wall roughness and interparticle collisions are important even at low solid loadings. Therefore, their influence must be included in the modeling with a stochastic, hard-sphere model, as described by Oesterlé and Petitjean (1993). In interparticle and particle-to-wall collisions, perfectly elastic collisions were assumed.

As demonstrated by Laín et al. (2008) the wall roughness plays a vital role in the dispersion of particles in pneumatic transport systems. In order to account for such effects, we implemented the model proposed by Sommerfeld and Huber (1999), to represent the effects of surface asperities on the particle flow. Other explanations about the Lagrangian model can also be found in Souza et al. (2014).

3. Materials and Conditions

The experimental investigations were made in the Experimental Unit of Ducts and Cyclones (EU-DC), as shown in the Figure 1. A Pitot tube (01) is connected to a differential pressure transmitter to measure the inlet mean gas-phase velocity; the gas flow rate was kept constant and promoted by an exhauster (10). The solid-phase is loaded into the system by a controlled rotary valve (06). Particles are separated by means a cyclone (08) and a bag filter (11). The pressure measurements, target of this study, were obtained with a pressure transducer located at the end of the 2 m long, 0.1 m i.d. upper horizontal pipe (07).

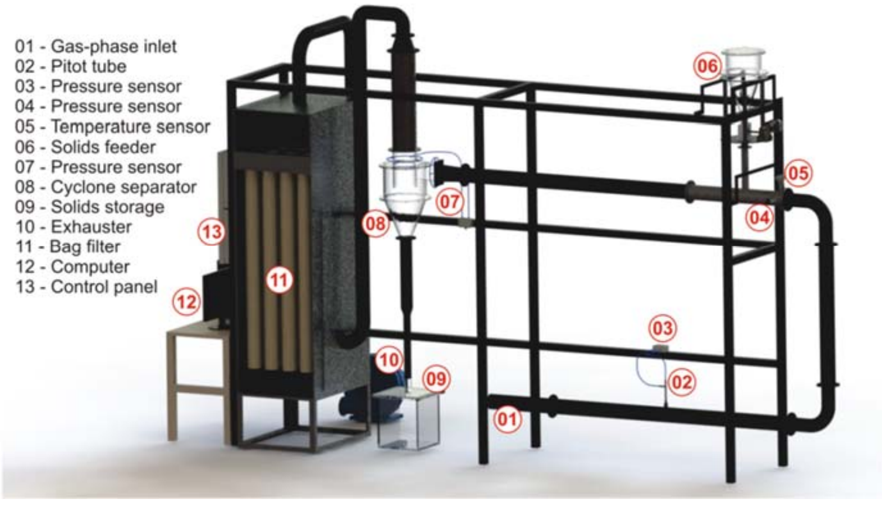

Figure 1: Schematic sketch of the Experimental Unit of Ducts and Cyclones (EU-DC).

Experiments were carried out according to the conditions showed in Table 1. The pressure data was collected at a rate of 1,000 Hz for 60 s at each particle material – both classified as Geldart "A" – and solids mass loading, η. An A/D converter, USB-6000 from National Instruments, a computer and a self-developed LabView program were used to data acquisition. The gas-phase Reynolds number based on the integral scale was kept $Re = 60{,}000$, for atmospheric air at 25 °C.

Table 1: Particle materials and experimental operational conditions.

Case	Material	$\rho_p(kg/m^3)$	$d_p(m)$	$\eta(kg_p/kg_g)$
A	(Clean flow)	-	-	0.00
B	FCC catalyst	1,400	72E-6	0.05
C				0.20
D	Glass beads	2,500	190E-6	0.05
E				0.20

In the Euler/Lagrange simulations, all the cases were reproduced computationally. The domain was simulated from the vertical pipe section, as showed in the detail of Figure 2. The hexahedral mesh has approximately 137,000 nodes. Nearly 50,000 computational particles are injected and tracked throughout the domain. Approximately 25,000 time steps are necessary for the particles to leave the domain. The particle time step used was 0.0001 s; 100 coupling iterations are carried out. Both the numerical mesh as the number of computational particles and the coupling iterations do not influence the solution. It is worth mentioning that the models employed in the UNSCYFL3D code were validated previously (Souza et al., 2012).

4. Results and Discussion

In order to reveal features of the phase interactions in gas-solid turbulent flow, the wall-pressure fluctuations at the end of a horizontal pipe, with two different particle materials and mass loadings were analyzed experimentally. First, the simulations evidenced that particles affect the flow pattern therefore modulate the gas phase turbulence. Figure 2 present the impact of phase interaction, material and operational conditions on the velocity profiles and the normalized particle concentration verified by CFD, measured at the end of the pipe. It is notable that the particles are concentrated at the half pipe bottom due to the gravitational force. The modification of gas-phase behavior is hard to understand by means RANS solutions, because of the lack of detailed information. Therefore, an experimental investigation is needed and the pressure fluctuations analysis is a good way to do this.

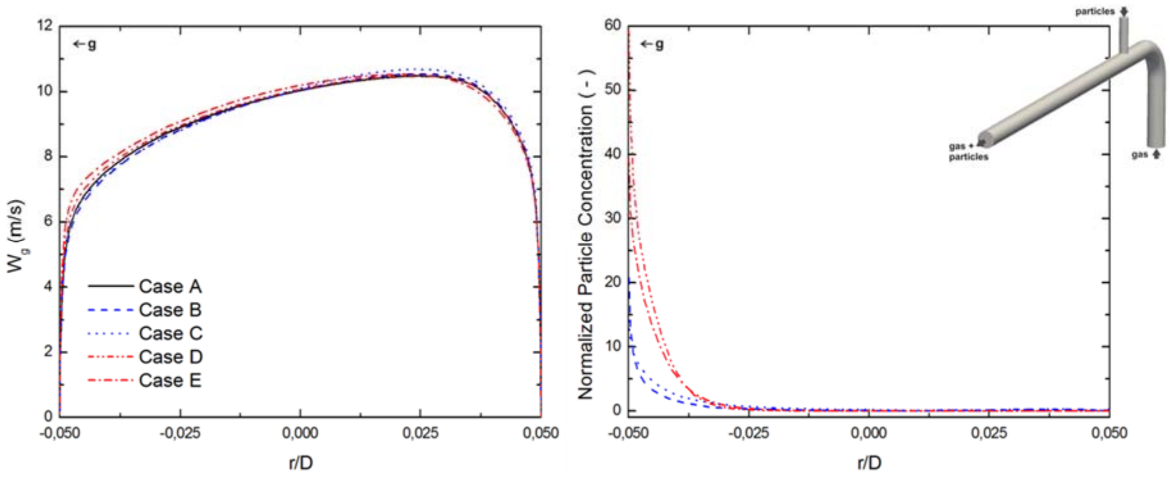

Figure 2: Mean axial gas-phase velocities (left) and normalized particle concentration (right): effects of material and operational conditions.

The pressure variation results from many mechanisms of gas-solid interaction, which occur at whole energy spectrum in different ways. To verify which frequencies are most affected, a multi-resolution wavelet transform was applied. The components of wall pressure fluctuations from wavelet level 1 to 8 are presented in Figure 3: a comparison between the time-behavior of clean flow (Case A) and the cases with highest mass loadings (C and E) within different scale bands. It is less evident the energy distribution than expected. Coefficients d1

(500 - 1,000 Hz) and d4 (62.5 - 125 Hz) have greater fluctuation, as seen in Figure 4, then the pressure fluctuation increase is not monotonic with decreasing scales.

Large peaks nearly periodic are found at the lower frequency, the approximation coefficient (a8, 1.95 Hz). These peaks suggest the occurrence of dune flow pattern: positive peaks represent a passing dune and negative ones, an interval between two successive dunes.

Making a comparison between all cases frequency ranges, we find that the presence of particles in the flow attenuates the pressure fluctuations, i.e. the clean flow has higher pressure fluctuation at all scales, except for the case B in the d8 coefficient. It is more clearly verified in Figure 4, which present the fluctuation pressure mean standard deviation of each detail coefficient. Curiously, the intermediate scales (d4) are so affected as the smaller time-scales (d1), although the last ones are less visible in Figure 3. Furthermore, the time-scales with 250 - 500 Hz have the lowest pressure fluctuations and the lower impact of particles modulation in the flow.

Therefore, the wavelet MRA indicates that the meso-scales are greatly affected, probably due to the fluid-like behavior of the solid-phase. In other words, the clustering phenomenon is one of the most responsible for the turbulence modulation. Similarly, individual particles modulate the spatial micro-scales by crossing the turbulence structures.

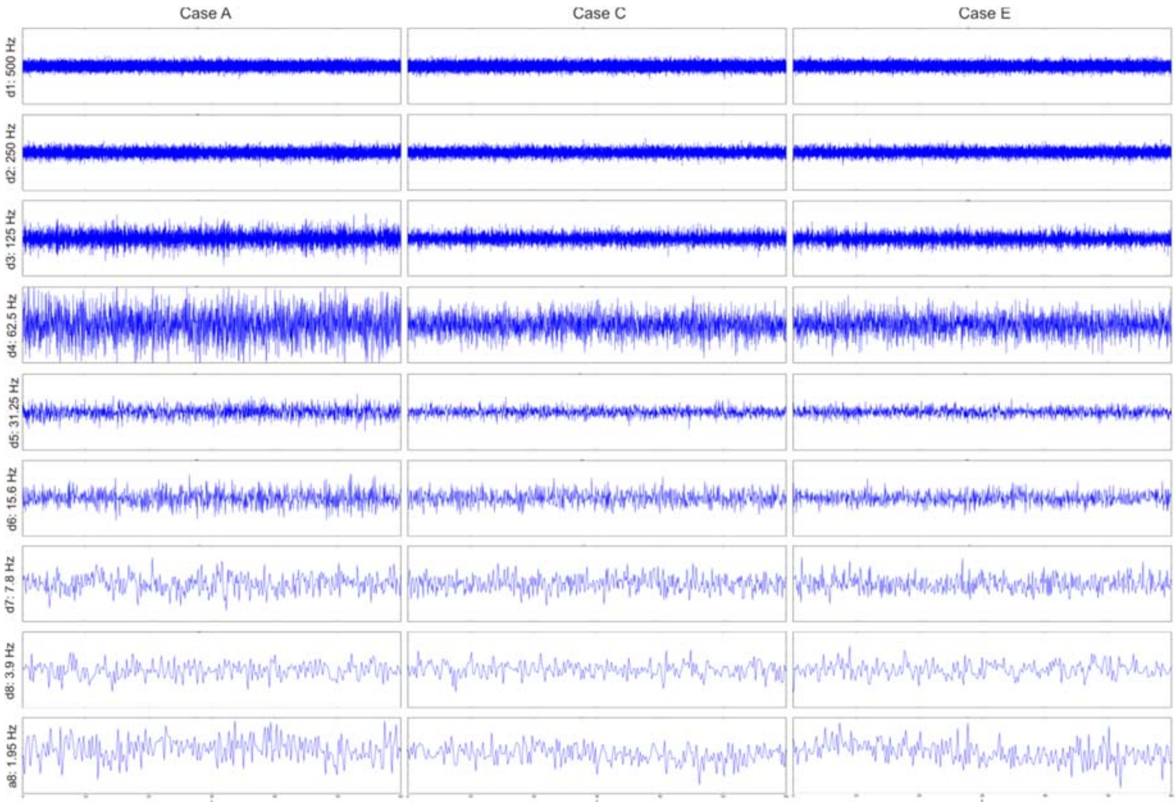

Figure 3: Wavelet multi-resolution analysis of fluctuating pressure at the horizontal pipe: cases A, C and E.

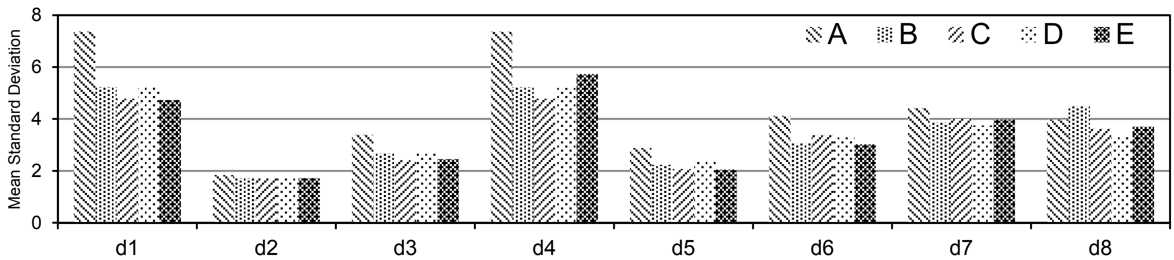

Figure 4: Experimental mean standard deviation of each detailed MRA coefficient, for each case.

5. Conclusions

The gas-solid turbulent flow in a horizontal pipe was analyzed. CFD simulations with the Euler/Lagrange approach and wavelet multi-resolution analysis were applied. Then the mean standard deviation of each wavelet coefficient was calculated. The main conclusions can be summarized as follows:

1. The gas-phase turbulence modulation by particles was evidenced in its velocity profiles;
2. Wavelet MRA of the experimental wall-pressure fluctuations showed that the reduction of the variability is not monotonic from de highest time-scales to the lowest ones; the meso-scales (62.5 - 125 Hz) have considerable energy;
3. The presence of particles in the flow attenuates the pressure fluctuations, i.e. the clean flow has higher pressure fluctuation;
4. Spatial micro-scales and meso-scales are de most affected scales of the energy spectrum in these operational conditions.

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