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Hydrodynamic Characterization of the Biomass Combustion in a Pilot Scale Fluidized Bed Combustor

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Hydrodynamics of fluidized bed combustors may be optimized promoting the establishment of "Gulf Stream" circulation patterns of fluidized particles to contrast the self-segregation of high-volatile fuel particles during devolatilization. The present study is aimed at characterizing bed hydrodynamics in a pilot scale fluidized bed combustor revamped to optimize combustion of high-volatile solid fuels. Time-resolved pressure signals measured at different locations in the bed and in the plenum were analyzed in the time and frequency domains. Results were compared with qualitative characterization of fluidization patterns by visual observation of the bed surface.

1. Introduction

Self-segregation of fuel particles during devolatilization is detrimental to efficient and trouble-free operation of fluidized bed combustors (Bruni et al., 2002). The axial segregation of fuel particles may be effectively contrasted by promoting vigorous circulation of fluidized solids (i.e. vortices at the reactor scale). Merry and Davidson (1973) suggested to induce vortices of scale comparable with the bed height ("Gulf Stream") by means of uneven distribution of fluidizing gas through the distributor. The hydrodynamics of bubbling fluidized bed has been typically characterized by time-averaged and dynamic analysis of pressure signals measured both in the plenum and inside the bed. However, the interpretation of time-resolved pressure measurements is not a trivial issue. Indeed, the nature of pressure fluctuations is the result of both global and local hydrodynamic phenomena related to the fluidized bed (van Ommen et al., 2003; Zhang et al., 2010) - bed oscillation, bubbles generation and eruption, bubbles coalescence and bubble passage (Musmarra et al., 1995) – as well as to the plenum-bed dynamic coupling (Johnsson et al., 2002). The hydrodynamics of fluidized beds is often investigated working out time-resolved pressure signals in time, frequency and phase-space domains as reported in different review papers (Johnsson et al., 2000; Sasic et al., 2007; van Ommen et al., 2011). This study aims at characterizing the hydrodynamics of a pilot scale fluidized bed combustor (FBC) revamped to optimize high-volatile solid fuel combustion with a focus on the establishment of "Gulf Stream" flow patterns. The FBC was equipped with a windbox splitted into two concentric sections: gas stream flow rates fed at the two sections were measured and controlled. The hydrodynamic behavior of the pilot scale FBC at ambient conditions and during the combustion of wood pellets was characterized by analyzing time-resolved pressure signals measured at different locations in the bed and in the annular section of the plenum in time and frequency domains. The dynamics of the bed was analyzed as a function of both mean fluidization velocity (U) and "partition ratio" (U_c/U_a), the ratio between the gas flow velocities in the core and annulus sections of the plenum chamber, respectively.

2. Experimental

2.1 Experimental Facility

The pilot scale 200 kW FBC (Figure 1) was used to carry out experimental campaigns at ambient conditions and during the combustion of wood pellets. The AISI 310 stainless steel fluidization column had

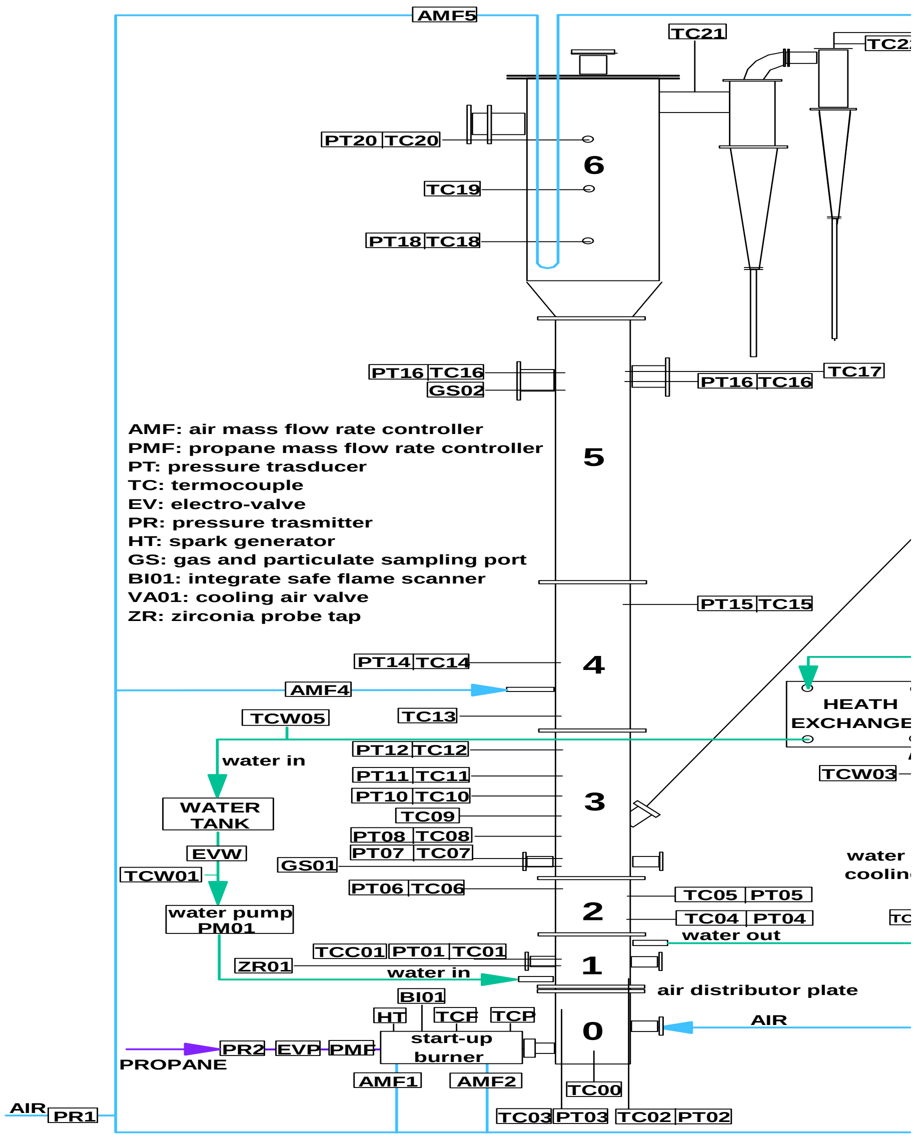

Figure 1: Schematic representation of FBC-370.

a circular section (370 mm ID) for almost all its height (5.05 m) whereas the upper part of freeboard was characterized by ID of 700 mm and height of 1.85 m (total height of 6.9 m). The lower section of the column was equipped with a windbox splitted into two concentric sections: the core (annulus) section characterized by the 30 % (70 %) of the fluidized column cross-section. The distributor plate is equipped with 55 bubble caps. The fluidization column was fitted with several ports for temperature, pressure, and gas concentration probes. Two cyclones are used for flue gas de-dusting. A probe is installed at the exit of the second cyclone for gas sampling. The entire vessel is thermally insulated by a ceramic wool blanket. The heat exchange is accomplished thanks to: i) a water-cooled external jacket for a height of about 0.3m from the distributor plate; ii) an array of horizontal bayonet-type tubes whose adjustable penetration into the bed controls the heat removal rate; iii) an air-cooled exchanger located inside the upper part of the freeboard (ID 700 mm) to prevent the operation of cyclones at high temperature. The cooling air can be used as fluidizing gas to quicken the fluidized bed heating during plant start-up. The FBC is equipped with a continuous over-bed feeding system. Fuel particles are fed by means of a belt-type device which is held up by a mass balance to measure the fuel mass flow rate. Particles fall down directly on the bed surface at an elevation from distributor plate z = 1050 mm. The start-up is accomplished thanks to a propane premixed burner located into the annulus section of the plenum. Figure 2 reports a schematic representation of the diagnostic apparatus. Pressure inside the bed were measured by 2 probes located at an elevation from distributor plate z = 170 mm. The probes were made of AISI 304 stainless steel tubes (4/6 mm ID/OD): the “core” probe was located at the center of the core section, the “annulus” probe was

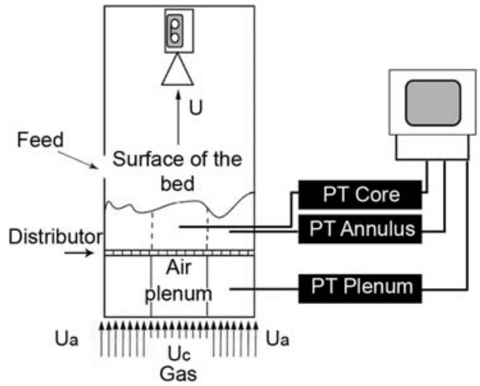

Figure 2: Schematic representation of FBC-370 diagnostic apparatus

located at the medium radius of the annulus section. Fine mesh net was located at the tube tip to prevent solids flow in the probe tube. Plenum pressure measurement was accomplished by means of a pressure probe located in the annular region of the windbox. Visual observations of the bed surface were possible through a quartz window located at the top of the column and video recordings were made using a Canon XH-A1 video camera. Piezoresistive transducers (DRUCK PMP 5063) were adopted to measure the time-resolved pressure signals. A National Instruments 9215 16-bit simultaneous analog input module - coupled with a National Instruments cDAQ-9174 USB chassis - was used as A/D converter. Each time series was sampled at 1 kHz for 120 s Bed material was quartz (0.950 mm Sauter diameter, U_{mf}=0.5 m/s at ambient conditions). The bed inventory was kept constant at 40 kg, corresponding to a static bed height of 0.28 m. Tests were carried out at four values of U: 0.7 m/s, 0.8 m/s, 1.0 m/s, 1.2 m/s. The fluidized bed dynamics was analyzed as a function of the partition ratio, U_c/U_a. Combustion tests using wood pellets as fuel were carried out at a mean fluidizing velocities of 0.8 m/s; fuel mass rate was adjusted to work with a constant air excess (45-50 %). The dynamics of the bed was analyzed as function of the partition ratio, U_c/U_a. Temperatures and pressures are measured in various points of the fluidization column. Flue gas are sampled at the exhaust and gas concentrations were measured by on-line gas analyzers (ABB AO2020). All the measurement signals are on-line monitored and recorded using a data acquisition system.

2.2 Data analysis procedure

Pressure time series were analyzed in time and frequency domains. Time domain analysis: the average absolute deviation and the average cycle frequency (evaluated as the inverse of the average cycle time) were calculated. The first one is a robust invariant which quantifies the average amplitude of fluctuations even if the probability distribution of the time series is not very similar to a normal distribution, whereas the second one is a measure of the time scale of the signal. Frequency domain analysis: Power-Spectrum-Density (PSD) function of the pressure signals measured inside the bed (calculated using Welch’s method) were decomposed - according to the method proposed by van der Schaaf et al. (2002) - into two components: the coherent part (fluctuations measured also in the plenum) and the incoherent part. The incoherent spectrum of the two pressure signals sampled inside the bed was further decomposed (van Ommen et al., 2003) into two sub-parts: the “joint incoherent” part, that represents the local fluctuations registered by both the signals inside the bed, but not in the plenum, and the ”exclusive incoherent” part, that represents the local fluctuations registered by only one of the two signals. Standard deviation of the different components of the PSD was also evaluated.

3. Results and discussion

3.1 Visual observations

Figures 3 and 4 show two sequences of snapshots of the bed surface captured at: ambient temperature, U=0.8 m/s, two partition ratio U_c/U_a=0.04 and 24.4. It can be observed that: i) for low values of U_c/U_a, bubble bursting was mainly concentrated in the annular section of the bed (Fig. 3), even if some bubble eruptions also occurred in the core region, probably due to meandering/coalescence of bubbles; ii) for high values of U_c/U_a an almost continuous ejection of bed solids in the central region of the fluidized bed was established, as a result of the eruption of multiple bubbles. Figure 5 shows two sequences of snapshots of bed surface during wood pellet combustion captured at U=0.8 m/s and for two different partition ratio, namely 0.2 and 43.7. It is noteworthy that the flames generated by volatile matter combustion are present mainly in the region where bubbles erupts more frequently: in the annular region for low values of partition ratio (Fig. 5a) and in the central region for high U_c/U_a (Fig. 5b). In the latter case, a quasi-continuous flare is evident in the splash zone. On the whole, the phenomenology during wood pellets combustion resembles the bubble flow hydrodynamics observed at ambient conditions

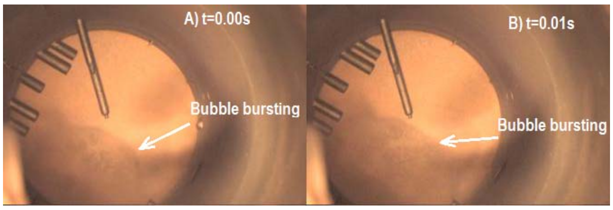

Figure 3: Images of bed surface captured at U=0.8 m/s and U_c/U_a=0.04..

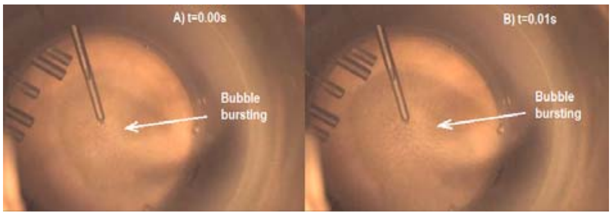

Figure 4: Images of bed surface captured at U=0.8 m/s and U_c/U_a=24.4.

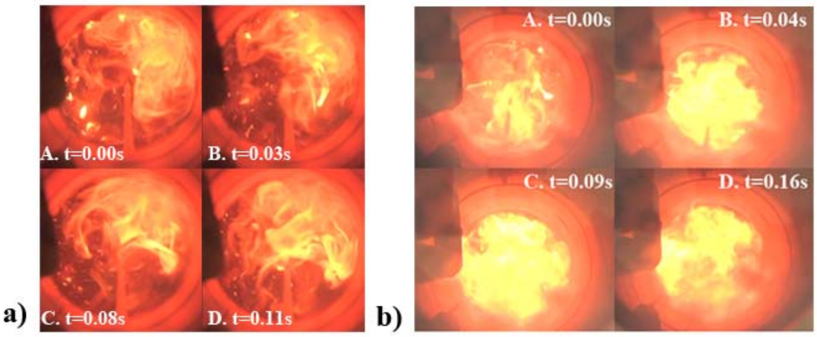

Figure 5. Images of bed surface captured during wood pellet combustion (U=0.8 m/s): a) U_c/U_a=0.2; b) U_c/U_a=43.7.

3.2 Frequency domain analysis

Figure 6 reports the PSD function of pressure signals measured in the core, annular and plenum section of the FBC as a function of U_c/U_a at U=0.8 m/s at ambient conditions (Fig. 6A, B, C) and during wood pellets combustion (Fig. 6D, E, F). The PSD analysis at ambient conditions highlights: i) a dominant frequency detected at 2–4 Hz; ii) a secondary frequency evident at 4–6 Hz; iii) the frequency and the power of the dominant phenomenon increased with U_c/U_a; iv) the power of the secondary frequency raised with U_c/U_a, more in the core section than annular and plenum sections. The PSD functions during wood pellets combustion were similar to those calculated at ambient conditions. The analysis of the PSD functions suggests that both dominant and secondary frequencies were related to coherent phenomena because they were also highlighted in the plenum. The dominant one was the "natural frequency" of the fluidized bed (the piston-like bed oscillation), whereas the secondary one was related to the eruption of bubbles in the core section. The relative relevance of the two phenomena accordingly changed with gas partitioning at the windbox: the eruption of gas bubbles at the surface of core section was more and more relevant increasing U_c/U_a when most of the fluidization air was fed to the core section in agreement with video recordings and snapshots reported in Figure 4 and 5b. The PSD analysis during wood pellets combustion confirmed observations reported for ambient conditions, except for a less marked effects of partition ratio on both the dominant and secondary frequencies.

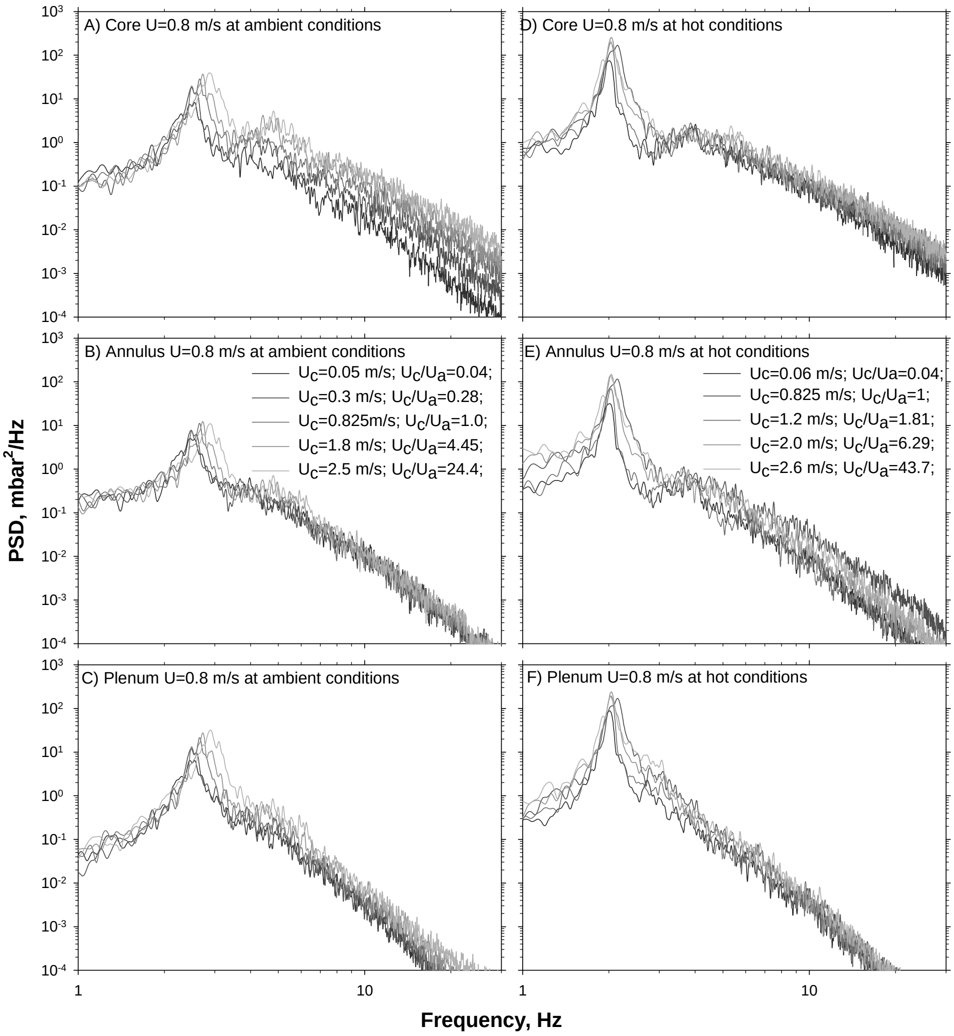

Figure 6: Power Spectrum Density (PSD) functions of pressure signals measured in core, annular and plenum sections for different values of U_c/U_a and U.

The spectral decomposition on basis of the pressure signals measured in the core, annular and plenum sections, allowed to calculate the standard deviations of the incoherent part of in-bed pressure signals (van der Schaaf et al., 2002) as well as the joint incoherent standard deviation (van Ommen et al., 2003) relative to incoherent part measured both core and annulus signals. The standard deviations are reported in figure 7 as a function of U_c/U_a. Data analysis for time series measured at ambient conditions highlights: i) the standard deviation of the "core" signal strongly increased with U_c/U_a; ii) the standard deviation of the "annulus" signal weakly decreased with U_c/U_a. The trends of standard deviations of time series measured during wood pellets combustion with U_c/U_a were very similar to those observed at ambient conditions. Taking into account that the incoherent part of pressure fluctuations represents the local dynamics nearby the pressure probes and the relative standard deviation represents its "power", the trend of standard deviations demonstrates that the number and the size of the bubbles can be raised only in core section increasing U_c/U_a, favoring the establishment of "Gulf Stream" circulation. At same time, the joint incoherent core-annulus standard deviation shows that a local phenomenon, (bubble passage or coalescence) occurring in the core section of the fluidized bed, generated a pressure wave of moderate power which increased with U_c/U_a

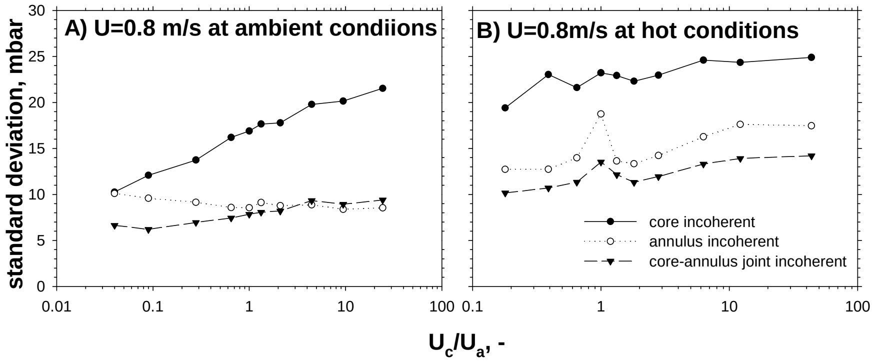

Figure 7: Standard deviations of incoherent part and joint incoherent part of core and annulus pressure signals as a function of U_c/U_a at ambient and hot conditions

4. Conclusions

The hydrodynamics of a pilot scale fluidized bed combustor (FBC) equipped with a windbox splitted into two separate and concentric sections (core and annulus) was characterized at ambient conditions and during the combustion of wood pellets by spectral analysis of pressure fluctuations measured in the core and annular section of the fluidized bed and in the plenum. Frequency domain and the spectral decomposition analysis demonstrated that "Gulf Stream" flow patterns can be established only for high values of partition ratio U_c/U_a when most of the fluidizing gas is fed to the core section both during the experimental campaign carried out at ambient conditions and during the combustion of wood pellets. This condition corresponds to the establishment of almost continuous ejection of bed solids in the central region due to the eruption of multiple bubbles which results to be a quasi-continuous flare during wood pellet combustion.

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