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Refereed Proceedings

2013

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HYDRODYNAMIC CHARACTERIZATION OF "GULF STREAM" CIRCULATION IN A PILOT SCALE FLUIDIZED BED COMBUSTOR

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ABSTRACT
The present study addresses the hydrodynamics of a pilot-scale fluidized bed combustor with a focus on the establishment of "Gulf Stream" circulation patterns as a solids mixing promoter. Time-resolved pressure signals measured at different locations in the bed and in the plenum were analyzed in the time, frequency and phase-space domains. Results were matched against qualitative characterization of fluidization patterns by visual observation of the bed surface.

INTRODUCTION
Self-segregation of fuel particles during devolatilization is detrimental to efficient and trouble-free operation of fluidized bed combustors (1). 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 (2) suggested to induce vortices of scale comparable with the bed height (“Gulf Stream”) by means of uneven distribution of fluidizing gas at 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 - bed oscillation, bubbles generation and eruption, bubbles coalescence and bubble passage (3-4) - as well as to the dynamic coupling between the plenum and the bed (5). The hydrodynamics of fluidized beds is often investigated by analyzing time-resolved pressure signals with the tools of spectral analysis (4,6-7). It exhibits the characteristics of low dimensional deterministic chaos (8), where the dynamic evolution of the system can be represented by a “strange attractor” in the phase-space. Takens (9) showed that the attractor could be reconstructed from a time series of only one characteristic variable of the system. Gas pressure fluctuations measured inside the fluidized bed were also used to reconstruct the attractor and to characterize fluidized bed dynamics by means of chaotic invariants such as the Kolmogorov entropy (K_{ML}) and the correlation dimension (D). This study aims at characterizing the hydrodynamics of a pilot scale fluidized bed combustor (FBC) with a focus on the intentional promotion of "Gulf Stream" flow patterns under a wide interval of operating conditions. A pilot scale FBC was revamped to optimize combustion of high-volatile solid fuels. The FBC was equipped with a windbox splitted into two concentric sections whence two streams of fluidizing gas were independently metered to the bed. The hydrodynamic behavior of the pilot scale FBC was

characterized by analyzing time-resolved pressure signals measured at ambient conditions along the fluidized bed and in the annular section of the plenum chamber in time and frequency domains and in the state space (5). The dynamics of the bed was analyzed as a function of the fluidization velocity (U) averaged over the cross section and of the "partition ratio" (U_c/U_a), i.e. the ratio between the gas flow velocities in the core and annulus sections of the plenum chamber.

EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental apparatus is an atmospheric pilot scale 200 kWth FBC (Fig. 1) operated at ambient temperature. The AISI 310 stainless steel fluidization column has a circular section of 370 mm ID up to 5.05 m above the gas distributor. The upper part of freeboard, 1.85 m high, enlarges to 700 mm ID. The total height of the combustor is 6.9 m. The lower section of the column is equipped with a windbox splitted into two concentric sections: the core (annulus) section

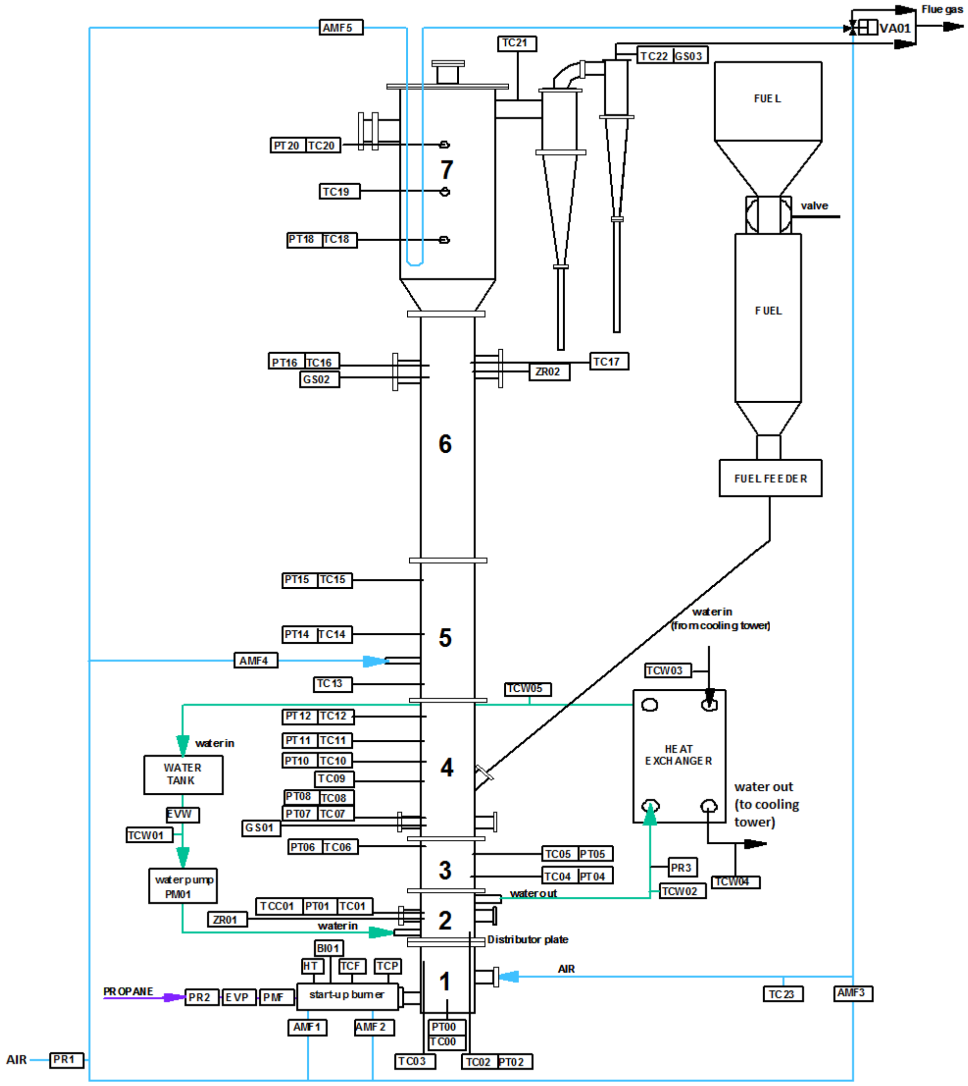

Figure 1 – Schematic representation of FBC-370. PT: pressure transducer. TC: thermocouple. GS: gas and particulate sampling port. AMF: air mass flow rate controller. PMF: propane mass flow rate controller. EV: electro-valve. PR: pressure transmitter. ZR: zirconia probe tap. VA01: cooling air valve. HT: spark generator. BI01: integrated safe flame scanner.

accounting for 30% (70%) of the column cross-sectional area. The distributor plate is equipped with 55 bubble caps. The fluidization column is fitted with multiple ports for temperature, pressure, and gas sensing probes. Figure 2 reports a schematic representation of the diagnostic apparatus. Pressure inside the bed is measured by 2 probes located at an elevation z = 170 mm above the gas distributor. The probes are made of AISI 304 stainless steel tubes (4/6 mm ID/OD): the "core" probe is located at the center of the core section, the "annulus" probe is located at a distance from the axis averaged between the inner and outer radii of the annular section. A fine mesh net is fitted to the tube tip to prevent solids flow into the probe. Pressure measurement in the plenum is accomplished by means of a pressure probe located in the annular region of the windbox. Visual observation of the bed surface is possible through a quartz window located at the top of the column and video recordings are made using a Canon XH-A1 video camera. Piezoresistive transducers (DRUCK PMP 5063) measured the time-resolved pressure signals. A National Instruments 9215 16-bit simultaneous analog input module - coupled with a National Instruments cDAQ-9174 USB chassis - is used as A/D converter. Each time series is sampled at 1 kHz for 120 s Bed inert material is quartz (0.950 mm Sauter diameter, U_{mf}=0.5 m/s). The bed inventory is kept constant at 40 kg, corresponding to a static bed height of 0.28 m. Tests are carried out at four values of U: 0.7 m/s, 0.8 m/s, 1.0 m/s, 1.2 m/s and variable partition ratio, U_c/U_a.

Data analysis procedure

Pressure time series were analyzed in time, frequency and phase-space 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 (10)) were decomposed - according to the method proposed by van der Schaaf et al. (7) - 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 (4) into two sub-parts: the "joint incoherent" part, that represents the local fluctuations registered by both signals sampled 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. The standard deviation of the different components of the PSD was also evaluated. The state space analysis of

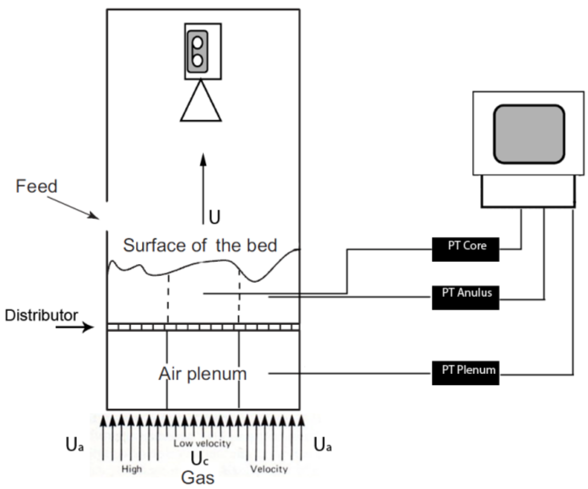

Figure 2 – Schematic representation of FBC-370 diagnostic apparatus.

pressure signals was implemented on the basis of the reconstruction of the attractor and of the evaluation of the chaotic invariants: the Kolmogorov entropy (the rate of loss of information of the system) estimated using a maximum-likelihood (ML) procedure developed by Schouten et al. (11), and the correlation dimension of the attractor (degrees of freedom of a dynamic system) estimated by the method developed by Schouten et al. (12) from a noisy time series. The non-linear analysis was performed by programs developed in Matlab™ 7.9.0, according to the algorithm described by vander Stappen (13). The program results were successfully compared to the outputs of the software package RRCHAOS (14), in order to validate the scripting in Matlab® 7.9.0.

RESULTS AND DISCUSSION

Visual observation of the bed surface

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 occurred also in the core region, probably due to meandering/coalescence of bubbles; ii) for high values of U_c/U_a almost continuous ejection of bed solids occurred in the central region of the fluidized bed, as a result of the eruption of multiple bubbles.

Frequency Domain Analysis of pressure signals

Figure 5 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 for two values of U: 0.8 m/s (Fig. 5A, B, C) and 1 m/s (Fig. 5D, E, F). The PSD analysis at U=0.8 m/s 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 in the annular and plenum sections. The PSD

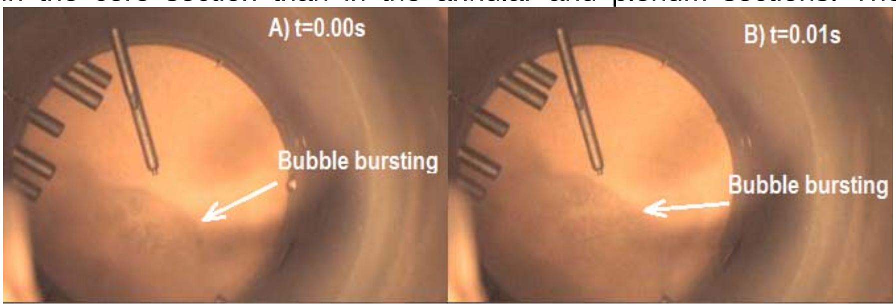

Figure 3 – Images of bed surface captured at U=0.8 m/s and U_c/U_a=0.04.

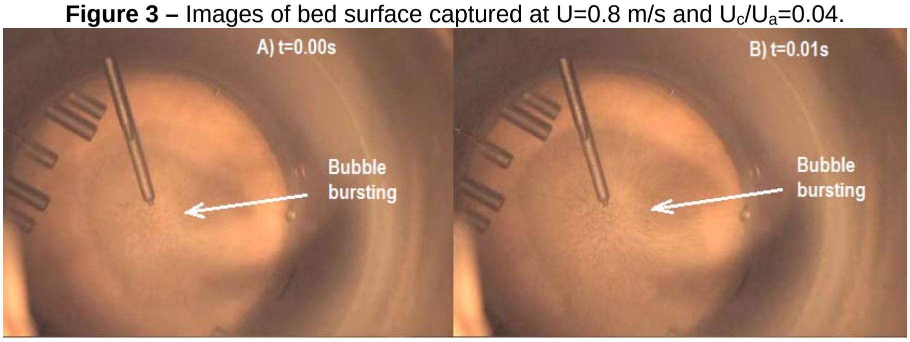

Figure 4 – Images of bed surface captured at U=0.8 m/s and U_c/U_a=24.4.

functions at U=1 m/s were similar to those calculated at U=0.8 m/s. The analysis of the PSD functions suggests that both dominant and secondary frequencies were related to coherent phenomena because they were also active 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 these phenomena changed with gas partitioning at the windbox: the eruption of gas bubbles at the surface of the core section became dominant as U_c/U_a was increased, when most of the fluidization air was fed to the core section. This finding agrees with qualitative patterns from video recordings and snapshots in Figure 4. The PSD analysis at U=1 m/s confirmed the features observed at U=0.8 m/s, with the exception of less marked effects of partition ratio on both the dominant and secondary frequencies.

Spectral decomposition 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 (7) as well as the joint incoherent

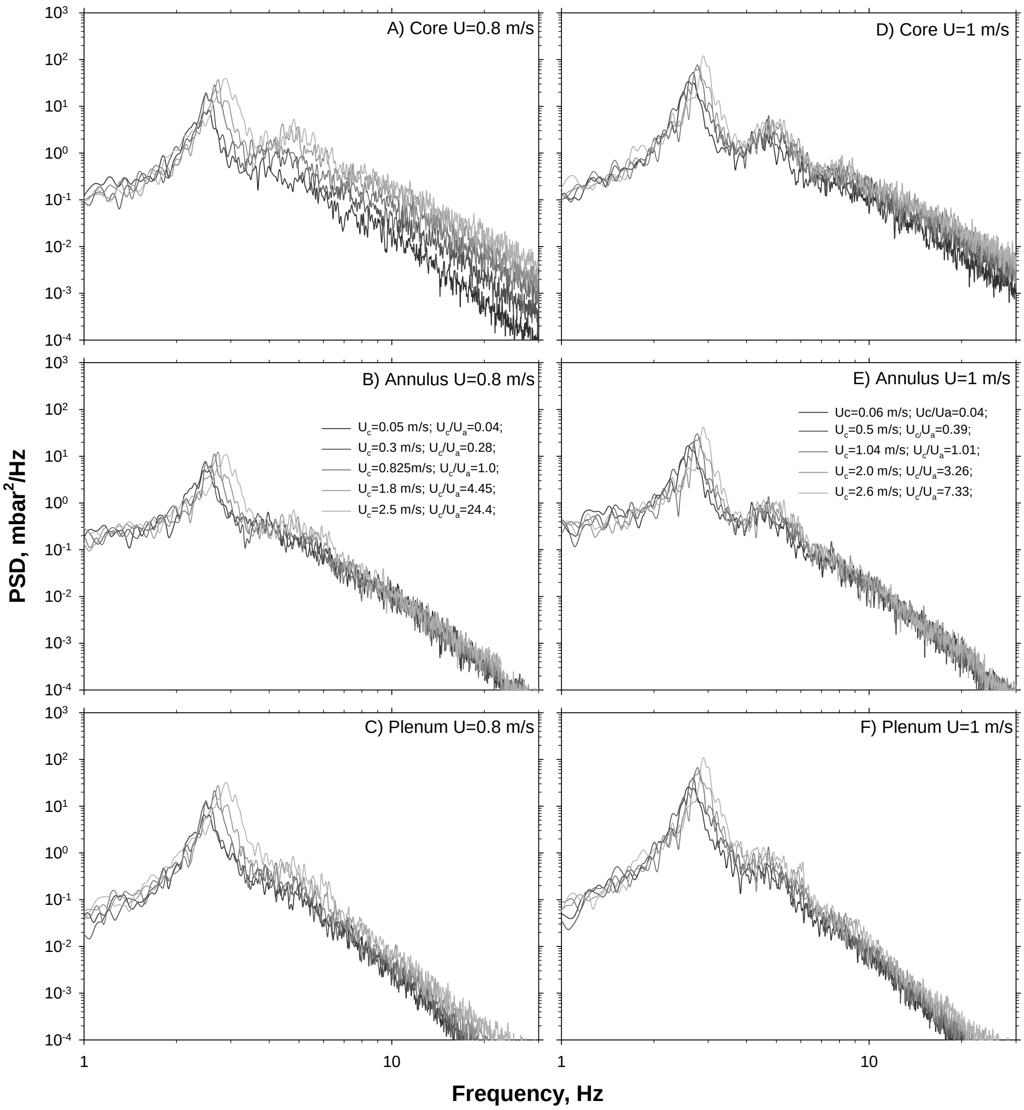

Figure 5 – Power Spectrum Density (PSD) functions of pressure signals measured in core, annular and plenum sections for different values of U_c/U_a and U.

standard deviation (4) relative to incoherent part measured both in the core and in the annulus. The standard deviations are reported in figure 6 as a function of U_c/U_a for different values of U. Data analysis at U=0.7 m/s 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. Increasing U, the trends of standard deviations with U_c/U_a were very similar to those observed at U=0.7 m/s, but the relevance of U_c/U_a on the incoherent part of the signals became less and less significant. Taking into account that the incoherent part of pressure fluctuations represents the local dynamics close to 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 selectively increased in the core section by increasing U_c/U_a, hence the establishment of "Gulf Stream". 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.

State Space Analysis of pressure signals

Figure 7 reports the Kolmogorov entropy (K_{ML}) as a function of U_c/U_a for different values of U, expressed in terms of bits of information lost per second (Fig. 7A and B) and bits of information lost per cycle (Fig. 7C and D). K_{ML} decreased with U both in the annulus and in the core: the predictability of the system increased, probably because the average bubble size increased with U. Indeed, the average absolute deviation of the signal increased with U, while the average cycle frequency remained almost constant. K_{ML} decreased with U_c/U_a in the annulus, whatever the reference time (Fig. 7A and C), indicating that bubbles erupted less frequently in the annular zone when the fluidizing gas was fed mainly in the core

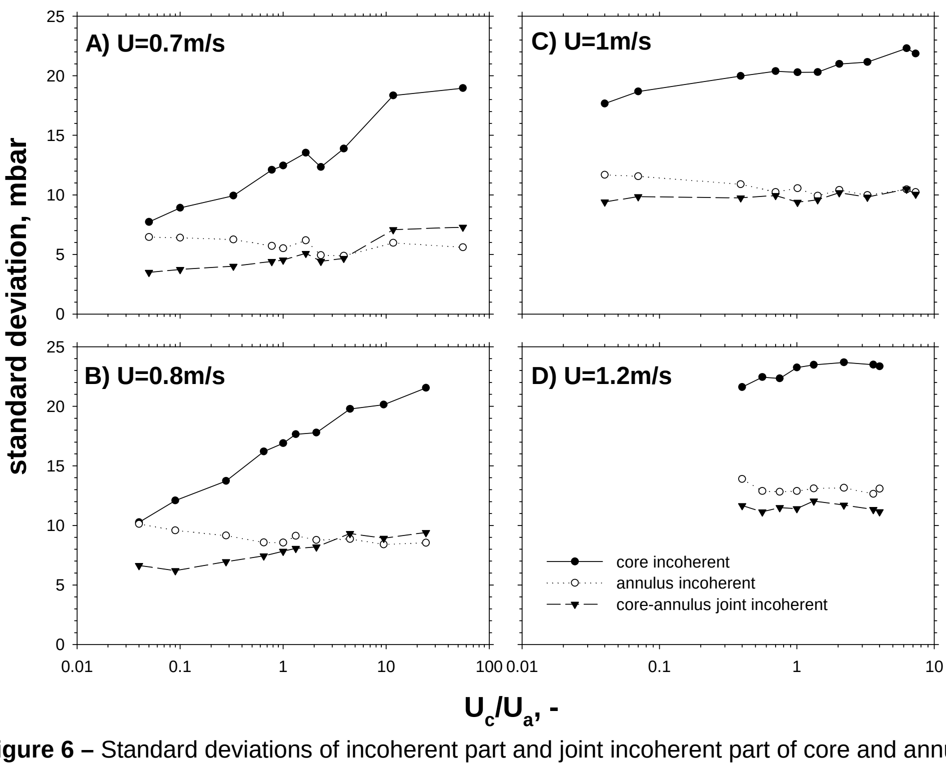

Figure 6 – Standard deviations of incoherent part and joint incoherent part of core and annulus pressure signals as a function of U_c/U_a for different values of U.

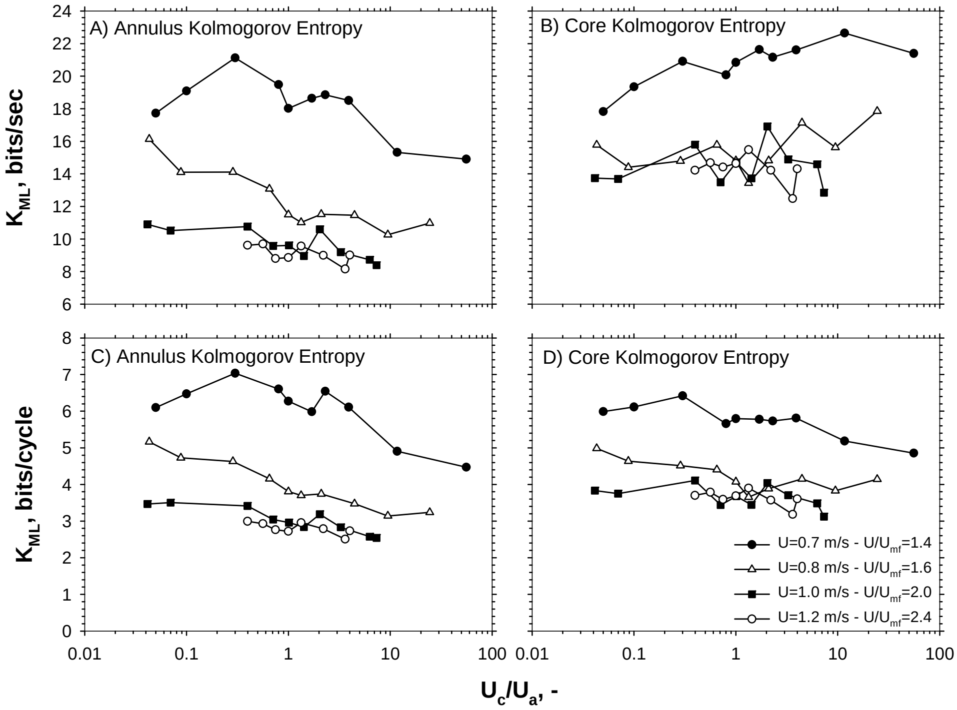

Figure 7 – Kolmogorov entropy as function of U_c/U_a, in bits per second (A, B) and in bits per cycle (C, D).

section of the windbox.

K_{ML} slightly increased with U_c/U_a in the core when expressed in bits/sec (Fig. 7B), and was nearly constant when expressed in bits/cycle (Fig. 7 D). These trends of K_{ML} indicate that the central zone of the bed became more 'chaotic' when U_c/U_a increased even if the loss of information during the average cycle in the core section did not change significantly. Since the rate of loss of information is mainly related to the eruption of bubbles at the surface of the bed, the Kolmogorov entropy measured by both probes indicates that: i) bubbles erupt more frequently in the core region for high values of the partition ratio; ii) bubble size in the core region is only slightly affected by U_c/U_a, because the entropy per cycle measured by the core probe is almost constant. Moreover, the core entropy is nearly always higher than the annulus entropy, when expressed in bits/sec (Fig. 7A and B): this implies that eruption of bubbles in core region is always present even for very low values of U_c/U_a. The presence of a radial profile of entropy (15) is consistent with the establishment of vortices of scale comparable with the bed height ("Gulf Stream"). The differences between the core and annulus entropies can be emphasized by tuning the partition ratio, enhancing the effect of these vortices.

CONCLUSIONS

The hydrodynamics of a pilot scale fluidized bed combustor (FBC) equipped with a windbox compartmented into a core and an annular sections was characterized at ambient conditions. The tools were: a) visual observation of the fluidization patterns at the surface of the bed, and b) spectral and non-linear analysis of pressure fluctuations measured in the core and annular section of the fluidized bed and in the plenum. Frequency domain and state space (Kolmogorov entropy) analysis proved to be effective tools to detect the establishment of "Gulf Stream" flow patterns. These could only be established for high values of the partition ratio U_c/U_a when most of the fluidizing gas is fed to the core section.

ACKNOWLEDGMENT
The support of Mr. A. Cammarota and of Miss E. Caccavale is gratefully acknowledged for the set-up of the experimental apparatus and for the analysis of pressure signals, respectively.

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