CHARACTERIZATION OF FLOW REGIMES IN A COLD CIRCULATING FLUIDIZED BED

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Abstract. *Circulating fluidized bed technology has been developed so far in a variety of industrial processes offering highly desirable characteristics such as: temperature uniformity, optimum gas–solid contact, good heat and mass transfer, higher and more efficient processing capacity compared to other technologies concerning process like coal combustion. A series of experiments were conducted in a Circulating Fluidized Bed (CFB) installed at the Laboratory of Thermal Processes and Environmental Engineering (PROTEA) at UNICAMP. A switching automatic system was developed for static pressure measurements in the CFB loop using remote control. The automatic system is composed of an electronic control card for solenoid valves, pressure transducer, data acquisition board and a computer. The average temperature of the main column during the experiments was around 383 K and Geldart B particles were used as solid material. The CFB loop is composed by a main column (4 m length and 0.102 m internal diameter), cyclone, sampling valve, standpipe and a solids circulation device called L-valve. Pressure profiles along the riser were settled by the static pressure measurement given by the switching automatic system involving 14 static pressure taps installed in the wall of the loop CFB. The influence of superficial gas velocity (0.7 to 6.0 m/s) and solids inventory (6.0 to 8.0 kg) on the CFB dynamics was verified using the automatic system. This work presents pressure and voidage profiles in the CFB system as a function of superficial gas velocity and solids inventory. Results allow the identification of the transition between transport regime and fast fluidization regime through the identification of the S-shape voidage profile.*

Keywords*: Circulating fluidized bed, pressure balance, fluidization regimes.*

1. INTRODUCTION

In 1921 Fritz Winkler presented the first demonstration of coal gasification using fluidized bed technology, Squires (1983). Circulating fluidized bed technology has been applied in a variety of industrial processes offering highly desirable features such as: temperature uniformity, optimum gas-solid contact, good heat and mass transfer, higher and more efficient processing capacity compared to other technologies such as bubbling fluidized bed concerning the coal combustion process. Fluidized beds have been used in a variety of catalytic and non catalytic process including: oil catalytic cracking (Berguerand and Lyngfelt, 2008), combustion, gasification and pyrolysis of solid fuels, naphthalene oxidation, mineral calcination, urban and industrial waste incineration (Mukadi *et al*., 1999), drying, heating and cooling of particles, tablets coating and metals surface treatment (Barletta *et al*., 2006). Currently, considerable efforts are focused in coal combustion (Basu, 2006), biomass and waste for energy generation (Barisic *et al*., 2006; Tourunen *et al*., 2009).

In the literature, several studies are presented concerning the dynamics of circulating fluidized bed systems based on static pressure measurements along the loop as reviewed by Smolders and Baeyens (2001). The flow behavior inside the loop depends on particle characteristics (diameter, density and sphericity), fluid properties (density and viscosity), column geometry (diameter and length) and operational conditions (gas velocity, temperature and pressure). Different fluidization regimes from bubbling fluidized bed to pneumatic transport are possible depending on these factors (Adánez *et al*., 1993; Smolders e Baeyens, 2001; Monazam *et al*., 2005; Mitali *et al*., 2008; Qi *et al*., 2008).

According to observations of Smolders and Baeyens (2001), the axial profiles can be classified into three types: I, II and III as shown in Fig. 1. Type I shows a profile where after the acceleration region of the solids there is a dilute phase to the top of the main column. In Type II, the voidage profile resents a S-shape meaning that the bed has an acceleration region located at the base of the main column, followed by a dense phase plus a region of acceleration before the dilute phase at the top of the column. Condition II is defined by the author as the beginning of the fast fluidization regime, obtained for superficial gas velocities above the transport velocity U_{TR}. Type III shows a region of acceleration followed by a dense region to the top of the bed.

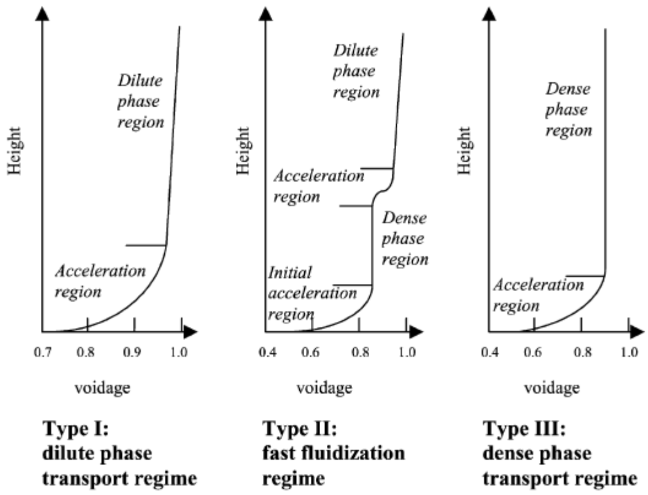


Figure 1. Classification of the voidage axial profiles
(adapted from Smolders and Baeyens, 2001)

Ishii *et al.*, (1992), Adánez *et al.* (1994), Monazam *et al.* (2005) and Mitali *et al.* (2008) agree that the fast fluidization regime occurs when the gas velocity is above the transport velocity U_{TR}, where an S-shaped profile is observed.

This work presents experimental results of pressure and voidage profiles as a function of gas velocity and solids inventory in order to find the transport velocity and the fast fluidized bed operational conditions for the studied system.

2. MATERIAL AND METHODS

The bench-scale circulating fluidized bed studied consists mainly of two parallel columns (riser and downcomer), a cyclone, a sampling valve for solids circulation rate measurements, and an L-valve as solid circulation device. The system includes auxiliary equipment that consists of solid supply system, roots-type blower to provide fluidized air, blowers, heat exchangers, electric heater, liquefied petroleum gas (LPG) combustor and a bag filter for fine particulates retention. The air velocity was obtained through an orifice plate meter constructed according Draft International Standard ISO 5167 - 1980 which provides an uncertainty of ± 0.1 m/s. Experiments were conducted using industrial quartz sand (density ρ_s=2525 kg.m^{-3}, mean diameter d_p=312.7 μm) as solid material. A scheme of the CFB loop is shown in Fig. 2.

2.1 Main column of the Circulating Fluidized Bed System

The combustor of CFB system, which is characterized by a sand flow loop is composed by the principal column or riser, cyclone, solids sample valve, downcomer and L-valve. It was manufactured in stainless steel AISI 310 allowing operations at temperatures up to 1173 K. The riser has a circular cross section with 0.102 m internal diameter and 4 m length.

2.2 Pressure measurement system

The static pressure measurements are distributed throughout the CFB loop and were assessed by 14 static pressure taps (10 taps in the main column and 4 taps in the standpipe), with nomenclature VS-1 to VS-14. The pressure measurement system is composed of five parts: the first part consists of a copper tube bent in spiral, with the aim of reducing the temperature of the gas-solid flow; the second part consists of a cleaning system installed in a PVC connection (Y-type) which has injection of compressed air in one of the branches avoiding the clogging of the pressure tap and in the other ramification a T-shape filter made in PVC, filled with cotton in its upper part in order to avoid the passage of solids into the pressure transducer. The third part consists of a reservoir where the filtered solids are collected; the fourth part is a connection with a hose which transports the gas to the manifold. The hoses that come from each pressure tap are carried to solenoid valves made by Schrader Bellows, fifth part of the pressure measurement system. The solenoid valves are installed in two manifolds interconnected in parallel. Figures 3a and 3b show the pressure measurement system and the solenoid valves respectively.

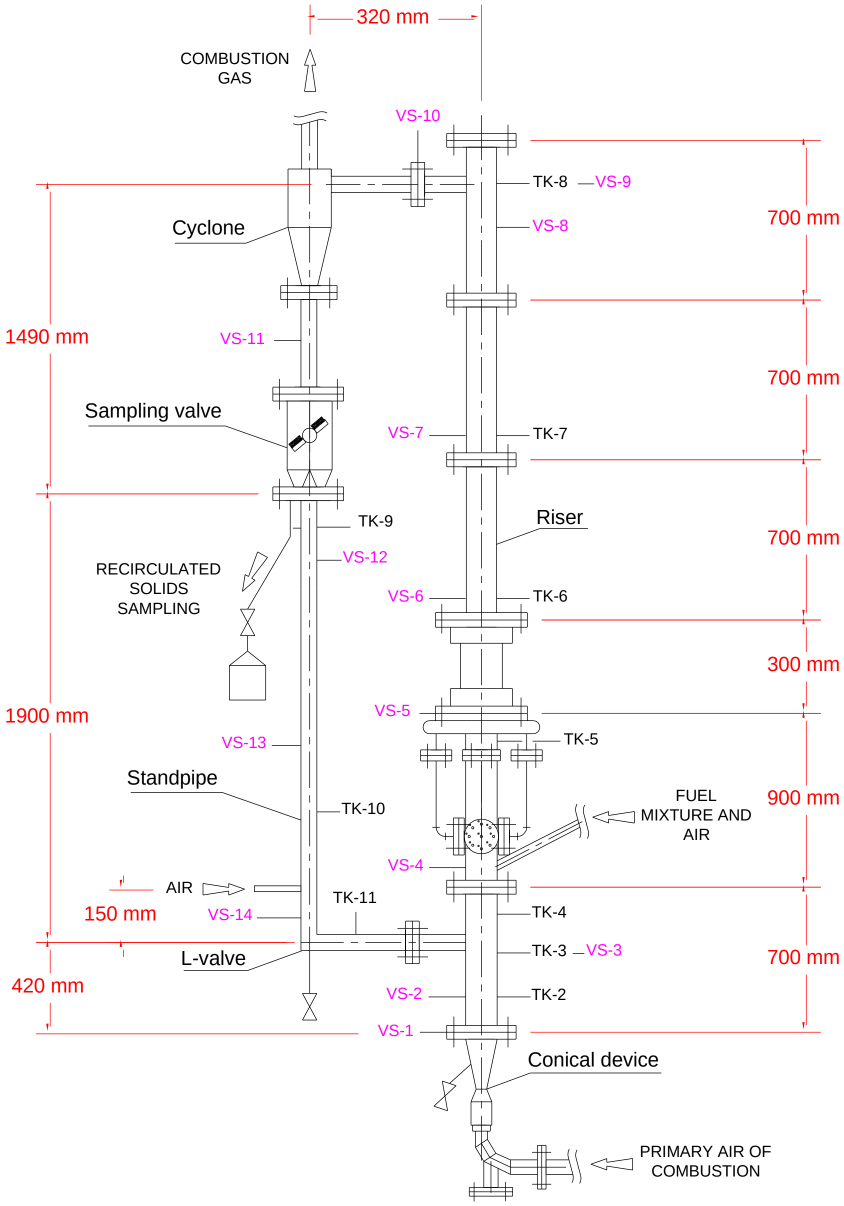


Figure 2. Circulating fluidized bed loop.

Figure 3. Pressure measurement system: (a) filtering and cleaning system; (b) solenoid valves

2.3 Acquisition data system

The acquisition data system is a remote station with three parts: board acquisition data NI USB-6255 series from National Instruments, computer with Labview 8.5™ software and electronic control of the solenoid valves. It is used to control the solenoid valves allowing obtaining the values of the 14 pressure taps through the CFB and acquiring the signals from the pressure transducer reference Rosemount 3051. Experiments were conducted at 383 K, as mean riser temperature, in steady state regime. Superficial gas velocities in the range of 0.7 to 6.0 m/s and solids inventory from 6.0 to 8.0 kg were used in the performed tests. Data acquisition used a frequency of 1000 Hz and the sampling data acquired were 20000 points. Figures 4a, 4b and 4c shows board acquisition data NI USB-6255 series from National Instruments, a computer and electronic control of solenoid valves and the pressure transducer respectively.

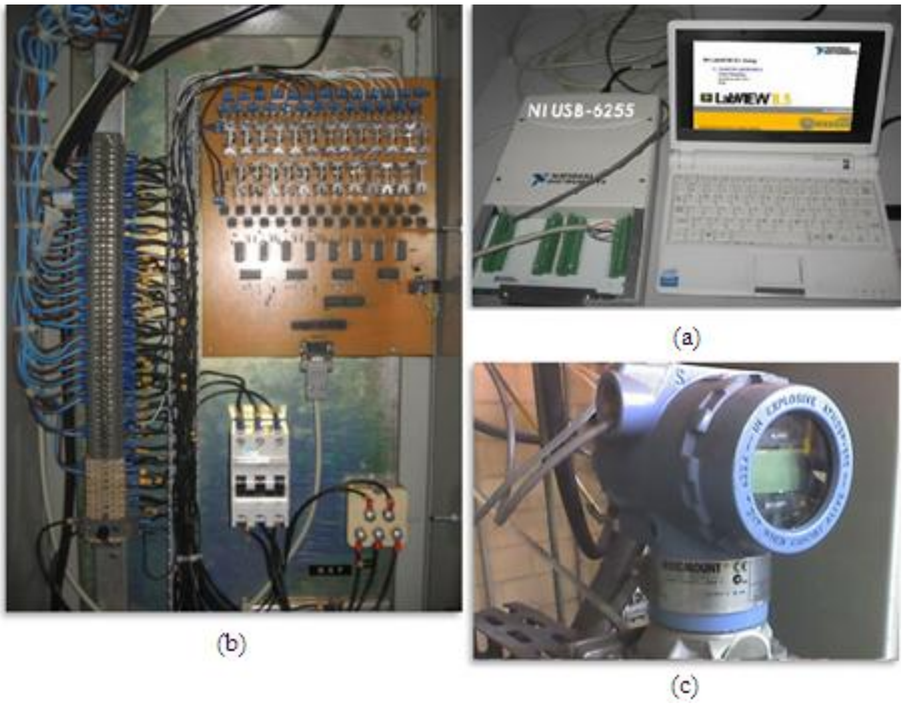


Figure 4. Acquisition data system: (a) board acquisition data; (b) electronic control of solenoid valves; (c) pressure transducer.

3. RESULTS AND DISCUSSION

3.1 Influence of the air velocity

The superficial air velocity in the circulating fluidized bed was progressively increased from 0.7 to 6 m/s during these experiments, maintaining the solids inventory constant in 6 kg. The static pressure measurements were taken with the automatic system over the CFB loop. The uncertainty of pressure measurements were ± 0.8 Pa. Figures 5 and 6 shows the pressure profile along the CFB loop obtained from experiments for each studied gas velocity. Figure 5 presents pressure profiles for velocities from 0.7 to 3.0 m/s where it can be noticed that for velocities above 3 m/s, there is significant solids circulation, characterized by the pressure increase in the L-valve. Figure 6 shows pressure profiles for velocities from 3.7 to 6.0 m/s, where the solids circulation was significant concerning all tests. Results show that increasing the gas velocity, the amount of solids in the standpipe increases, as well as the pressure in the L-valve. This behavior occurs due to the pressure balance established in the CFB loop.

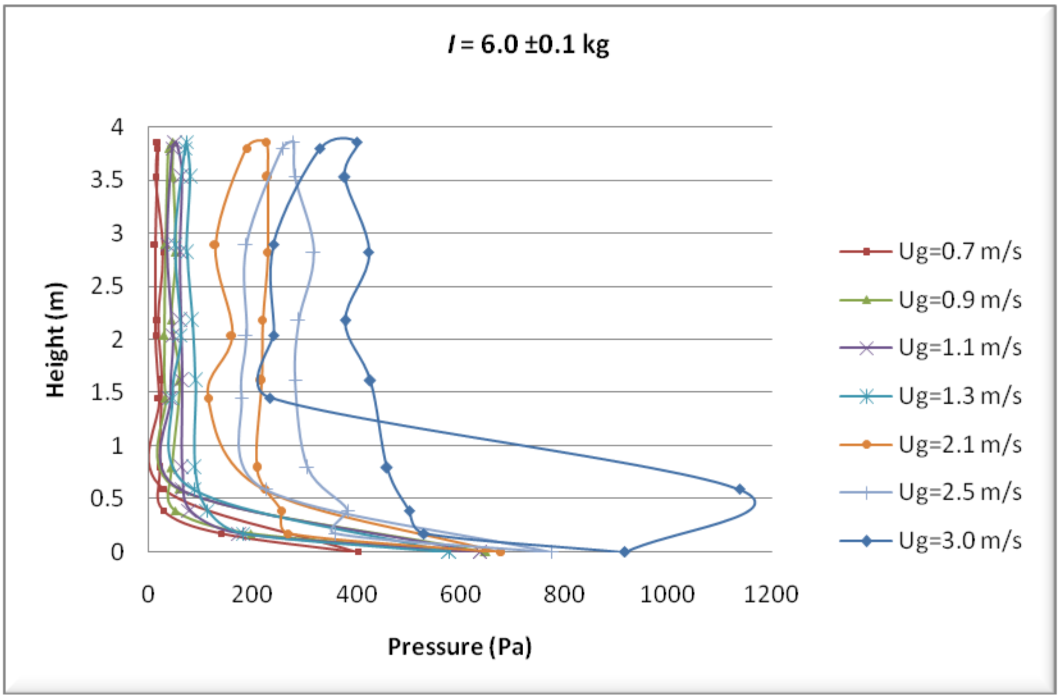


Figure 5. Influence of the superficial gas velocity on the pressure profile in the CFB loop ($0.7 \leq Ug \leq 3.0 \pm 0.1$ m/s)

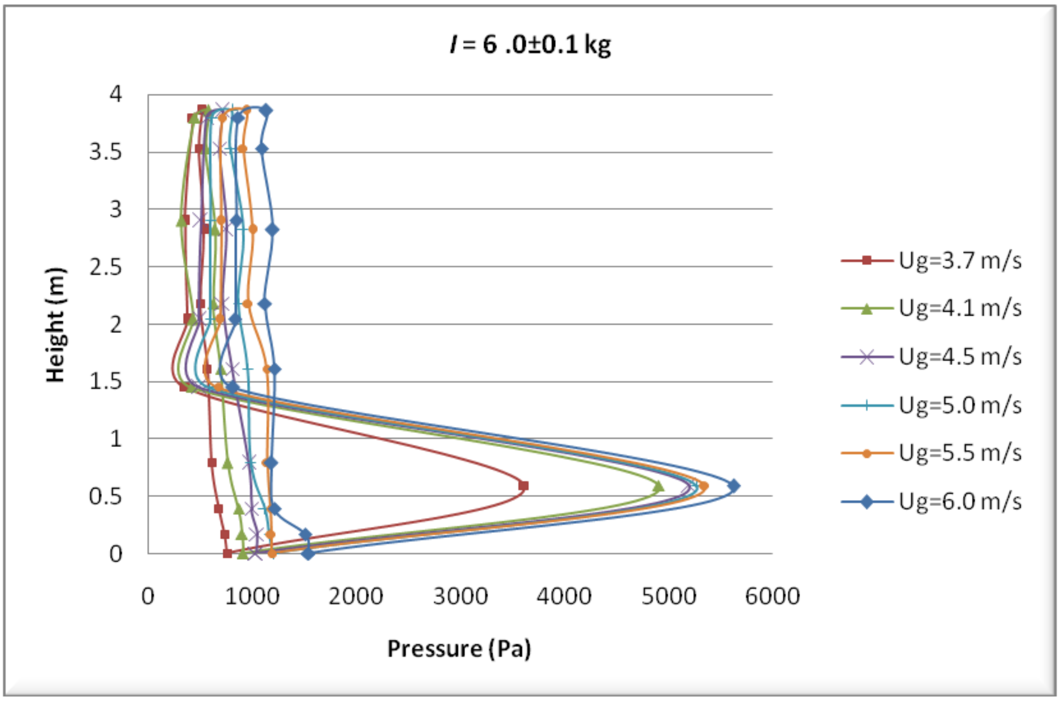


Figure 6. Influence of the superficial gas velocity on the pressure profile in the CFB loop ($3.7 \leq Ug \leq 6.0 \pm 0.1$ m/s)

The axial voidage profiles were obtained from Eq. (1), that is often used for CFB systems where the pressure drop in the riser is attributed to the weight of the solid particles. The friction effect of gas-wall and solid-wall was neglected.

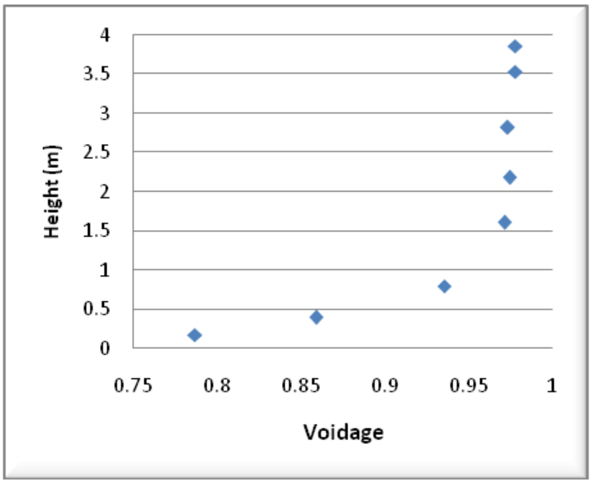
$$\varepsilon = 1 - \frac{\Delta P}{\Delta Z \rho_s g} \qquad (1)$$

The uncertainty analysis for voidage was ±0.01 according to Holman (1994), considering the uncertainty of the pressure measurements (Eq. 2).

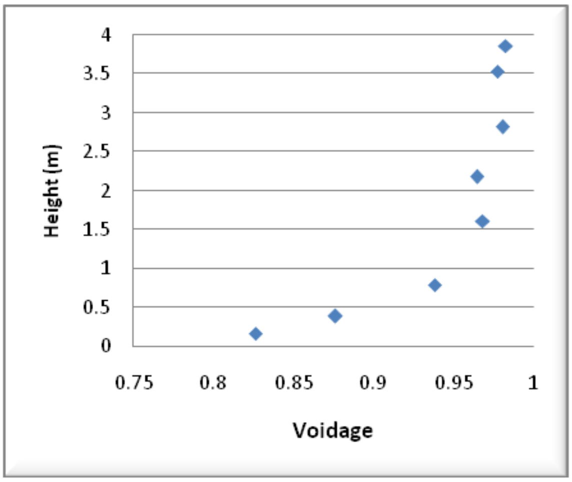
$$\mu^2_{(\varepsilon)} = \sum_i \left(\frac{\partial \varepsilon}{\partial \Delta P} \right)^2 \mu^2_{(\Delta P)} \tag{2}$$

Where $\mu_{(\Delta P)}$ represents the uncertainty of the measured pressure drop between two adjacent pressure taps in the riser.

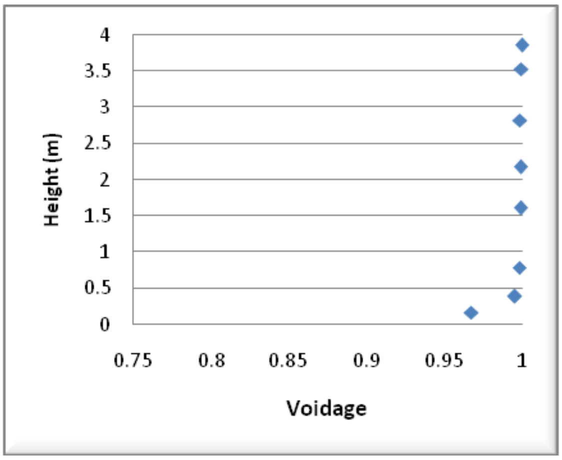
Figures 7a, 7b and 7c show the influence of superficial gas velocity on the axial voidage profile along the riser. Increasing the superficial gas velocity, it can be observed an increase on the voidage along the riser due to the reduction of solids concentration in the dense region of the CFB and increase on entrainment rate. The transition to the fast fluidization regime, occurred at a gas velocity around 3.7 m/s denoted by the presence of the S-shape in Fig. 7b.



(a)Ug=2.5 ±0.1 m/s



(b) Ug=3.7 ±0.1 m/s



(c) Ug=6.0 ±0.1 m/s

Figure 9. Influence of the superficial gas velocity on the riser voidage profile (I=6 ±0.1 kg)

3.2 Influence of the solids inventory

Figure 8 exhibits the influence of the solids inventory (6 to 8 kg) in the CFB loop for a constant value of the superficial gas velocity. Results show in Fig. 9 that the pressure drop in the L-valve increases almost linearly with the increasing solids inventory. It was observed that the superficial velocity and the solids inventory affects the pressure profile and the analysis of these profiles allows to obtain the transition velocity from turbulent regime to fast fluidized regime where the solid circulation is significant. These observations are in agreement with the works of Hirama and Takeuchi (1992), Rhodes and Laussman (1992) and Bi and Zhu (1993).

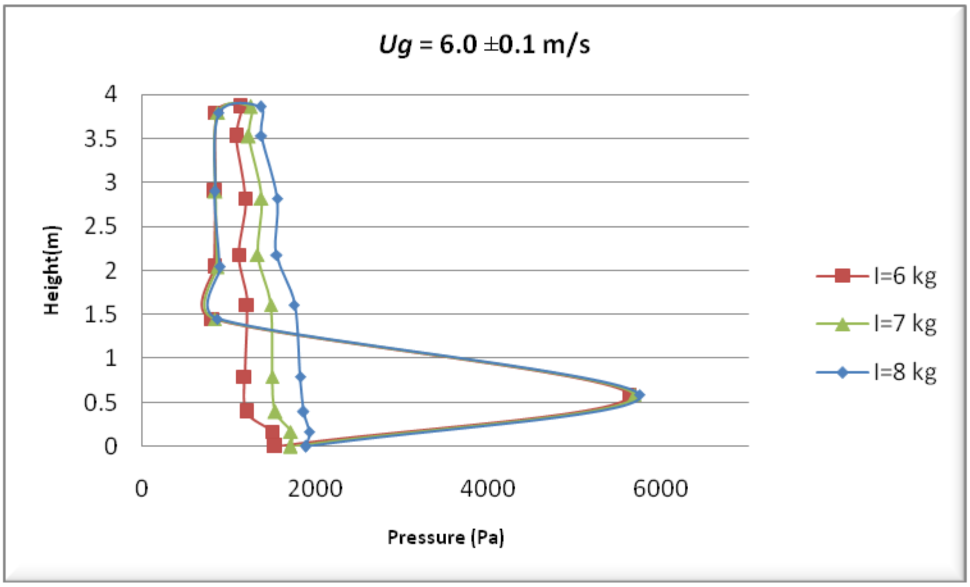


Figure 8. Influence of the solids inventory on the pressure profile along the CFB loop (6≤I≤8 ±0.1 kg)

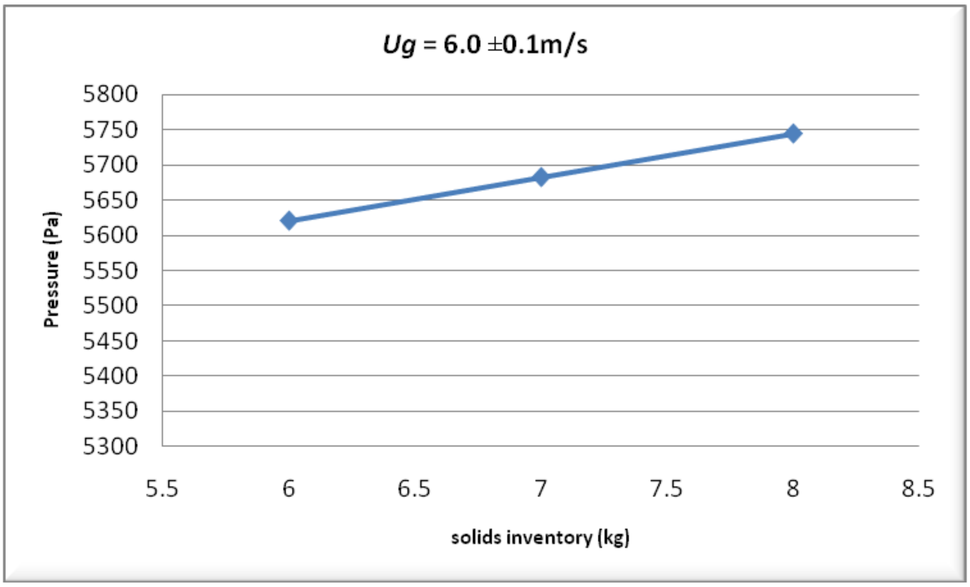


Figure 9. Influence of the solids inventory on the pressure in the L-valve (6≤I≤8 ±0.1 kg)

4. CONCLUSIONS

Pressure and voidage profiles along the CFB loop allow the determination of fluidization regime inside the riser and they are affected by the superficial gas velocity and solids inventory. Experimental results showed that a typical fast fluidization regime, concerning a solid inventory of 6 kg inside the CFB loop, was obtained for gas velocities around 3.7 m/s.

Pressure in the L-valve increases almost linearly with the increase of solids inventory in the CFB loop. Experimental voidage profiles show the S-shape that characterizes the fast fluidization regime.

Results obtained contribute for CFB knowledge and show data for the studied bench-scale system that are useful in order to reach a stable operation condition in the experiments.

5. ACKNOWLEDGEMENTS

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Notations

d_p	Mean Sauter particle diameter (μm)
g	Gravity acceleration (m/s^2)
I	Solids inventory (kg)
U_{tr}	Transport velocity (m/s)
U_g	Superficial gas velocity (m/s)
Z	Axial co-ordinates in the bed (m)
ΔP	Pressure drop across the bed (N/m^2)

Greek symbols

ε	Voidage (-)
ρ_s	Solid particles density (kg/m^3)

Subscripts

tr	Transport
g	Gas
p	Particle

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