EXPERIMENTAL STUDY OF CIRCULATING FLUIDISATION REGIMES WITH DENSE POWDER

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Abstract: The aim of this study is to get a better comprehension of gas-particles fluidisation regimes in an industrial boiler from a smaller pilot plant operating at ambient conditions. Experiments have been conducted in an experimental CFB loop with solid particles of high density in order to satisfy some similitude principle considerations.

Keywords: fluidisation, suspension, regime transition, choking, similitude.

INTRODUCTION

Fluidized beds are employed in a wide variety of applications such as combustors or chemical reactors, to name a few. In many commercial applications the fluidized bed employed has a large diameter and height and operates at high temperature and pressure. To properly design a fluidized bed the fluid dynamics must be well understood since it directly influences the bed performance. Designers are thus particularly concerned with the relationship between the performance of large commercial beds and the results obtained from much smaller pilot plants. There is a critical need to understand and predict the fluid dynamics of large fluidized beds; However, on the one hand there is a dearth of relevant information available in the field of large commercial beds; On the other hand there is a large amount of data and approximate analytical models based on results from small experimental beds. But, these data are collected under a fairly restricted range of operating conditions and, it is not obvious how the data can be applied to large commercial designs.

Boilers, which are the main focus of the present work, are normally operated with particles ranging from group B to group D in the Geldart classification. They usually have a square or rectangular cross section and are wider than the height of the bottom bed. These beds are of a non-slugging type. Our purpose is to have a better understanding of gas-particles fluidisation regimes in commercial boilers by operating smaller pilot plants at ambient condition. To be representative of a commercial bed, the smaller plant and the material used must have certain particular characteristic [1]. Among them is the ratio ρ_s/ρ_g [1] where ρ_s and ρ_g are the solid and gas densities respectively which must satisfy the relationship:

$$(\rho_s/\rho_g)_m = (\rho_s/\rho_g)_c \tag{1}$$

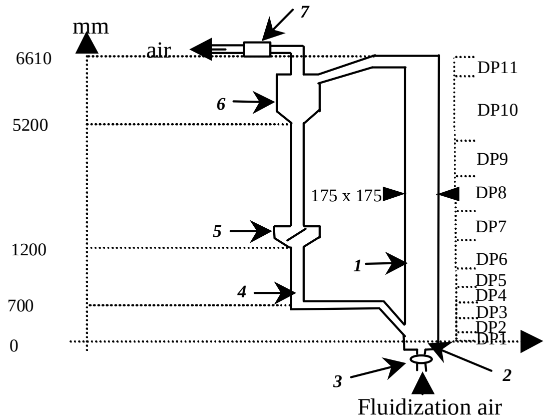
where the subscript m is for the model and c is for a commercial bed.

This is why the study has been conducted in an experimental CFB loop with solid particles of high density (bronze), as opposed to sand, glass beads or FCC which are usually encountered in literature.

Identification of the various fluidisation regimes have been made, similar to those done by other authors [2,3,4] by means of the pressure drop fluctuations analysis. Identified transition velocities are then compared with existing correlations.

EXPERIMENTAL FACILITIES

The experiments have been carried out in a pilot scale cold circulating fluidized bed, consisting of a riser column and a solids recycle system. The riser column walls are made of perspex, have a 0.175m × 0.175m (Fig. 1) square cross-section and from the fluidisation grid are 6.61m high to the roof. The exit riser is located at the top, to one side of the riser, with a 0.175m × 0.13m rectangular cross-section. The exit pipe forms a 90° angle with the riser axis. Gas-particle separation is obtained by means of a centrifuge cyclone, which directs the solid phase to the distributor via a solid flowmeter. The bed is supplied with air at ambient temperature by a booster pump via a fluidisation grid. Powder is introduced at the bottom of the riser, through the side wall, the solid flow rate in the loop is continuously indicated. The riser is equipped with 12 differential pressure transducers, which deliver a 4-20 mA signal proportional to the measured pressure. They can be connected as required to 50 pressure taps, 6mm diameter drilled through the perspex wall, uniformly arranged on the center line of the riser wall. There are also 2 absolute pressure transducers located at the top and bottom of the riser. Filters have not been used on the taps, which would prevent solid particles from getting inside the measurement line, but would also reduce the transducer sensitivity to dynamic pressure fluctuations. The pressure taps have been chosen as suggested by Clark *et al* [5] in order to guarantee the best response of the lines. The fluidisation velocity inside the riser u_0 is determined from the measurements of air mass flow upstream of the riser and the temperature and pressure inside the riser.



1 riser
2 fluidization grid
3 fluidization flow meter
4 solid screw feeder
5 solid mass flow meter
6 separator
7 filter

Figure 1: Experimental device.

Measurement accuracies are given in Table 1. These are mean values since they are dependent on the measurement range of the device and the measured value itself.

Solid mass flow rate (%)	Relative pressure (%)	Temperature (°C)	Air mass flow rate (%)	Fluidisation velocity (%)
5	1	0.5	1	2

Table 1 : Measurement accuracies.

Operating conditions are given in Table 2.

<table>
<tr><th colspan="2">Bed characteristics</th><th colspan="2">Material properties</th><th colspan="2">Operating conditions</th></tr>
<tr><td>height (m)</td><td>6.61</td><td>type</td><td>bronze</td><td rowspan="2">solid flux ($kg.m^{-2}.s^{-1}$) :</td><td rowspan="2">1.25 to 54.42</td></tr>
<tr><td rowspan="3">cross-section (m^2)</td><td rowspan="3">0.175× 0.175</td><td>density (kg/m^3)</td><td>8790</td></tr>
<tr><td>mean diameter (µm)</td><td>43</td><td rowspan="2">velocity ($m.s^{-1}$)</td><td rowspan="2">1 to 9</td></tr>
<tr><td>sphericity</td><td>1</td></tr>
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Table 2: Experimental conditions.

The differential pressure signals are acquired at 100Hz during 45 to 120 seconds, both for the riser segments defined between pressure taps, and for the total pressure drop. Acquisition duration has been adjusted based on the pressure drop fluctuation periods observed.

A mean value and standard deviation are calculated for each of these signals. The ratio of standard deviation to mean value (Normalized Standard Deviation, NSD) reflects variation in amplitude of the measured pressure fluctuations. By plotting graphs of the evolution of this quantity versus fluidisation velocity, it is possible to identify fluidisation regime transitions [4, 6].

In addition, visual observations were performed through the perspex walls of the riser to identify a change of the two-phase flow behavior with changing u_0. These observations were obtained in order to confirm fluidization regime transitions detected with NSD analysis.

EXPERIMENTAL RESULTS

NSD measurements at a constant mass flow rate (G_s) plotted versus u_0 fit the curves which present a maximum value for a specific fluidisation velocity u_c as shown in Fig. 2.

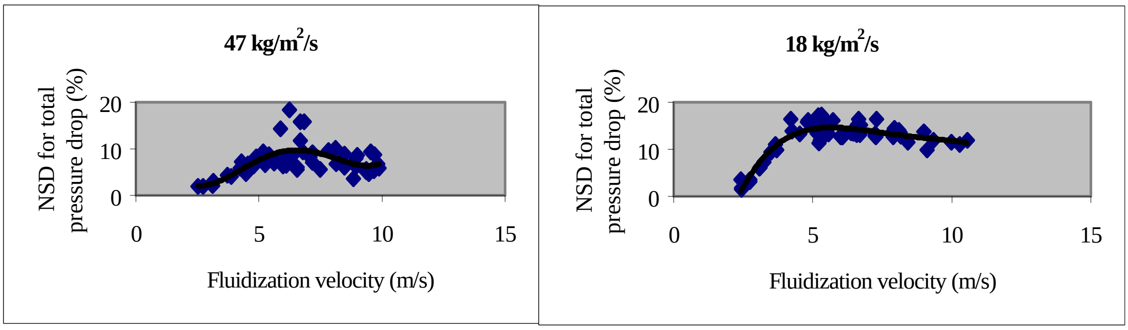

Figure 2 : Normalized standard deviation for total pressure drop in the riser versus fluidisation velocity for two different mass flow rates : 18 kg/m^2/s and 47 kg/m^2/s.

For the five values of G_s investigated, those specific velocities are identified as fluidization regime transitions when compared with visual observations. For G_s = 47 kg/m^2/s when the transition velocity u_c is greater than u_0, one can observe, through the bottom bed walls, the presence of clusters impinging and numerous trails spreading on the walls. The clusters and trails do not have a well-defined displacement: some of them go up, others down, and it is clear that some of them have a transverse velocity. These observations point out the existence of a splash zone over a dense bed, where the two-phase flow is the most turbulent. On the contrary, when u_0 is greater than u_c, clusters impinging on the walls are no longer observed. and only a few trails can be seen. Furthermore, it is important to note that, for the whole range of G_s and u_0 investigated, the bottom bed voidage was close to 0.95. Also, visual observations have shown, the existence of a boundary layer where particles flow down , close to the perspex walls and along the riser height. These observations show that pneumatic transport has not been reached since such a fluidization regime is characterized by a dilute bed with all particles flowing upward.

Moreover, at constant flow rate G_s and for the five values of G_s investigated, a minimum fluidization velocity $u_{0\,min}$ was found below which mass flow rate could not be maintained. When $u_{0\,min}$ was reached from higher values, the CFB flow, which was the densest and the most turbulent we could observe, suddenly broke down. No solid recirculation was possible (except with increasing u_0) and the riser presented two distinct regions. The first one, at the bottom of the riser, was a dense bed, which could be described as a bubbling bed with very few air bubbles. The second one, localized over the first one, was so dilute that it was hardly possible to detect solid particles being entrained to the top of the riser. Thus solid mass flow rate was zero. Those results were completed by investigation of G_s down to 1.25 kg/m^2/s in order to have a better description of this limit.

To summarize, two fluidization-regime transitions were observed under operating constant mass flow conditions: a turbulent/fast transport transition and, at lower fluidization velocity, a breakdown limit (in terms of fluidization velocity), at which sudden change from CFB to bubbling/fixed bed was observed, and under which constant mass flow rate could not be maintained. These transitions are discussed and analyzed in the following sections.

ANALYSIS AND DISCUSSION

Transition from a captive to a fast transport regime involves a turbulent regime, as observed by many authors [4, 7, 8, 9]: with the increase in u_0, the fluidized bed in the riser changes from a dense to a bubbly condition, and turbulence inside the riser consequently grows. This increase in turbulence is accompanied by variations in the density fluctuation amplitude. These density fluctuations can be quantified by riser wall pressure measurement, comparing the signals delivered by wall pressure transducers with those delivered by optical probes as shown by [9]. Thus the maximum standard deviation of total pressure drop in the riser corresponds to a maximum level of turbulence in the riser, associated with a specific velocity. This description is identical to our research findings. The upper bound, u_c, is related to the transition from turbulent to fast transport regime. At constant mass flow rate, below u_c, the gas-particle flow is turbulent and tends toward a fixed bed.

For values above u_c, as u_0 is increased, the turbulence then smoothly decreases while the fluidization regime is of a fast transport type and can tend toward pneumatic transport. The transition between a fast transport regime and pneumatic conveying is achieved at a characteristic velocity u_k. This could not be identified in the present work because it requires investigation at higher fluidization velocities than can be provided by our equipment.

For values below u_c, another specific velocity is reached when decreasing u_0. This corresponds to a sudden breakdown of the bed with no possible recirculation. This specific velocity $u_{0\min}$ has been called by many authors "choking velocity" [10, 11]. Bi *et al* [8] have proposed a review of choking description, pointing out that some choking occurrences can be induced by equipment-limited operating modes, while others are due to the suspension characteristics. It has been verified, in the present work, that the choking transition obtained was not of the first type by comparing the pressure balance in the CFB loop and upstream of the fluidization grid. The present choking transition is of the second type, the same as that observed by Chang *et al* [11].

1 Correlations for turbulent-fast regime transitions

Many correlations have been proposed for estimation of u_c and u_k, in the case of powders with $\rho_s < 4500 \mathrm{kg/m^3}$, fluidized in a pipe or vessel without solid recirculation. Most of them are expressed in terms of Archimede number Ar and Reynolds number Re, have been reviewed by Arnaldos *et al*.[12]. It is obvious that such correlations cannot fully describe transition regimes as long as a main parameter, such as solid mass flow rate is ignored.

Yang and Bai *et al* [13,7] have proposed correlations for such specific transition regimes velocities. A comparative summary of the different operational parameters and operating conditions is shown in Table 3.

Yang's and Bai's correlations for the transition of turbulent to fast fluidization are:

Yang *et al*: $$u_c = 1.463\sqrt{gD}\left(\frac{G_s D}{\mu}\frac{\rho_s - \rho_g}{\rho_g}\right)^{0.288}\left(\frac{D}{d_p}\right)^{-0.69} \mathrm{Re}_t^{-0.24} \qquad (2)$$

Bai *et al* $$u_c = 2.050\left(\frac{\mu}{\rho_g d_p}\right)\left(\frac{G_s}{\rho_s\sqrt{g d_p}}+1\right)^{0.793} Ar^{0.393} \quad (3)$$

where :

g = gravity acceleration, m/s^2
d_p = mean particle diameter, m
D = riser equivalent diameter, m
$Re_t = d_p u_t \rho_g / \mu$
u_t = terminal velocity of a single particle, m/s
μ = gas viscosity, Pa.s
$Ar = \rho_g g(\rho_p - \rho_g) d_p^3 / \mu^2$

Physical parameters and units	Yang *et al*	Bai *et al*	Present work
ρ_s , kg:/m^3	$794 < \rho_s < 1487$	$660 < \rho_s < 4510$	8790
d_p , μm	$85 < d_p < 325$	$33 < d_p < 1200$	40
D , m	0.030	$0.03 < D < 0.30$	0.1975
G_s , kg/m^2/s	$0 < G_s < 170$	$10 < G_s < 300$	$1.25 < G_s < 54.42$
u_0 , m	$1.7 < u_0 < 6.3$	$1 < u_0 < 12$	$1 < u_0 < 9$

Table 3: Application ranges for correlations proposed by Bai *et al* and Yang *et al* [7,13]

However these correlations make predictions which are closer to the choking velocity detected in the present work than to the specific velocities identified as the transition between turbulent and fast fluidization regimes. When reporting calculated specific velocities using the above correlations and the experimental points from this present work versus the solid mass flow rate G_s (see Figure 3), an under-estimation of 60% can be seen.

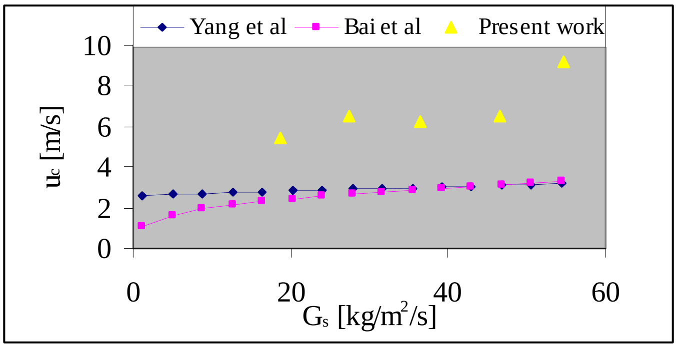

Figure 3: Comparison of different turbulent to fast fluidization transitions u_c versus solid mass flow rate G_s.

Two points can be put forward to explain this deviation : the solid density we use is out of the correlations' application range and that type of CFB is in terms of slugging or non-slugging systems. In fact, Yang's correlation has been calculated with 100% slugging systems data, and Bai's correlation with more than 77% slugging systems data. It is obvious that riser in which slugs can occur will present a transition from the captive to the fast regime which is different from those where slugs will not take place. Slugging systems are able to present high amplitude fluctuations in suspension density which appear during the turbulent regime. Dynamic fluctuations induced on pressure drop thus have very high amplitude, especially when slugs are of a plug type, alternating between very dilute and high particle concentrated waves. This kind of turbulent behavior cannot be observed in non-slugging systems (such as ours) and it could explain why the turbulent to fast transport regime transition is detected at a lower fluidization velocity for slugging systems.

2 Correlations for choking transitions

For choking transitions, the review of Bi *et al* [8] suggests that Yang's [10] and Bi's correlation [14] correspond to the type of choking encountered in the present work. They are respectively :

$$\frac{u_{ch}}{\varepsilon_{ch}} = u_t + \sqrt{\frac{2gD\left(\varepsilon_{ch}^{-4.7} - 1\right)\rho_s^{2.2}}{6.8110^5\ \rho_g^{2.2}}} \tag{4}$$

$$\frac{u_{ch}}{\sqrt{gd_p}} = 21.6\left(\frac{G_s}{\rho_g u_{ch}}\right)^{0.542} Ar^{0.105} \qquad \text{with } G_s = \left(u_{ch} - u_t\right)\left(1 - \varepsilon_{ch}\right)\rho_s \tag{5}$$

where : u_{ch} = choking velocity, m/s and ε_{ch} = voidage at choking

Chang *et al* [11] have found out that Yang's correlation (4) can be applied successfully to large-scale risers. Figure 4 shows how data from the present work is bounded by those correlations (4) and (5). We arrive at the same conclusions as Bi *et al* [8] who reported the over-estimation of correlation (4), while (5) under-estimates the experimental data. The prediction of these correlations can be considered satisfactory.

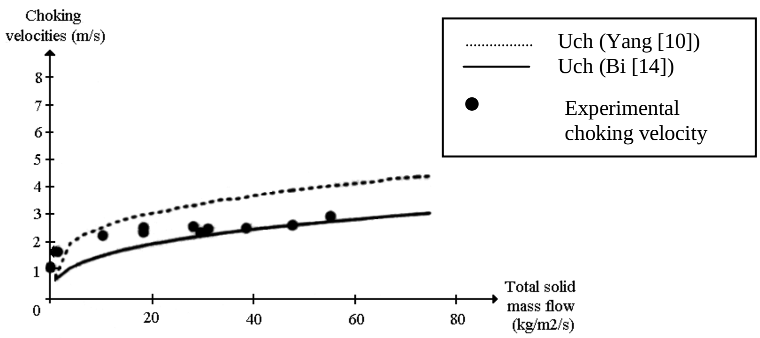

Figure 4 : Comparison of correlations for choking limits from Yang and Bi *et al*. [10,14] with experimental choking data of the present work

CONCLUSION

Experiments were conducted in a non-slugging CFB loop with solid particles of a higher density (bronze) compared to those encountered in literature (sand, glass beads or FCC). Bronze was chosen to yield, with ambient fluidization air, the same density ratio as the French industrial CFB combustors suspensions. Investigations were performed for a large range of solid mass flow rate and fluidization velocity. Analyses of the standard deviation of pressure drop fluctuations normalized with pressure drop amplitudes and visual observations have shown that :

- a choking velocity is found at low fluidization velocity and is associated with a sudden breakdown of flow and no possible solid recirculation,
- a turbulent to fast transport regime transition at higher fluidization velocities is identified, characterized by the maximum of a normalized standard deviation of pressure drop fluctuations.

While correlations in existing literature developed for recirculating loops can predict the choking limit encountered in the present work fairly well, experimental specific velocities identified for turbulent to fast transport transition are under-estimated by 60%.

Analysis and discussion imply that two parameters may explain this misprediction. Firstly, the density of the particles used in the present work is high and out of the correlations' application range. Secondly, the system type is non-slugging while correlations have been computed mainly with data from slugging systems.

These results show that the use of existing correlations to predict the transition from turbulent to fast transport regimes for large scale experimental CFBs or industrial units could yield to an under-estimation of this fluidization regime transition velocity. When an experimental facility must be in similitude with an industrial CFB, if the fluidization regime is to be retained as one of the similitude criteria, the existing correlations do not seem to be able to provide a suitable answer.

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