Vertical jet interaction for variable nozzle distance in a gas-solid fluidization bed.

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ABSTRACT: This study was a set of experiments in a rectangular fluidization bed with vertical and rectangular slots using particles type B and D of Geldart's classification of powders. Particle image velocimetry techniques, image analysis software and on-site measures were used to study the effect of the nozzle distance on vertical interacting jets, specifically, the amount of area of the bed fluidized and the jet penetration height. It was found that the nozzle distance does not significantly affect the area of particles fluidized, hence, two interacting jets fluidize the same area as two isolated jets because the coalescence of jets forms a single larger jet of double the size. On the other hand, the area fluidized seems to be directly proportional to the jet velocity; as the flow rate increases, the shape of the area fluidized modifies shrinking from the top and expanding to the sides, also increasing the total area fluidized with a maximum in the bed wall dimensions. The bed appeared to have a threshold for jet interaction at $(L-d_j)/d_j = 4.67$ and the dead-zones between jets seemed to disappear in an interacting situation because of circulation of air between the nozzles due to large bubbles forming at the bottom of the bed. The jet penetration height was directly proportional to the distance between jets, reducing as the nozzles become nearer and eventually being zero when both nozzles are in the same position. These findings are contrary to most of the models for jet penetration height for interacting jets, as they do not take the distance between nozzles in consideration. Sensible results were found in comparison with the correlations of Yates et al., 1995 and Wu and Whiting, 1987 on the jet penetration height of multiple jet systems for particles type B and D, respectively, with constant flow rate.

1 INTRODUCTION

Fluidization is a process in which a granular material is transformed from a solid and static state to a fluid and dynamic state. A column of fluid (liquid or gas) is passed through a packed bed of particles with enough velocity that induces the fluidization phenomenon. In this state of fluidization, particles do not behave as a solid anymore, they acquire a fluid behaviour [1].

The use of fluidization is extended in the industry, applied in fields such as chemical, environmental, pharmaceutical and food processing benefiting the production of detergents, pharmaceuticals, food and fertilizers by virtue of the distinguished gas-solid mixing and heat transfer properties of fluidized beds [2, 3]. However, previous research has focused on one single jet and the knowledge about the behaviour of multiple-jet fluidized beds and the interaction between jets is still limited [3].

1.1 Fundamentals

Pressure loss (ΔP) is experienced by a gas passing through a bed of particles due to the friction resistance, which linearly increases with the superficial fluid velocity (U). As U increases, the drag on the particles caused by the fluid also increases, arriving to a point in which the apparent weight of the particles in the bed equals the fluid drag, and the bed becomes fluidized. At this point, the superficial fluid velocity is known as minimum fluidization velocity, U_{mf}. Hence, equating the force balance in which the pressure drop is equal to the weight of the particles, the following expression is obtained [4]:

$$\Delta P = H(1-\varepsilon)(\rho_p - \rho_f) \tag{1}$$

For a bed of particle density ρ_p, fluidization fluid density ρ_f, bed depth H and voidage ε.

In order to derive an expression for the minimum fluidization velocity, it is used the Ergun equation [5]:

$$\frac{(-\Delta P)}{H} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U}{x^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_f U^2}{x} \tag{2}$$

Where x is granule or particle diameter.

Combining Equations (1) and (2), a definition for minimum fluidization velocity is obtained. The bed expands when $U > U_{mf}$ and after such expansion the excess of gas starts to form bubbles passing through the bed, at a gas velocity known as minimum bubbling velocity, U_{mb} [6].

Minimum fluidization velocity is also known as incipient fluidization and it is governed by particle size, density, and fluid properties; increasing with particle size and density particularly. Geldart empirically studied the fluidization properties in ambient conditions for different types of particles giving as a result four different groups [7]:

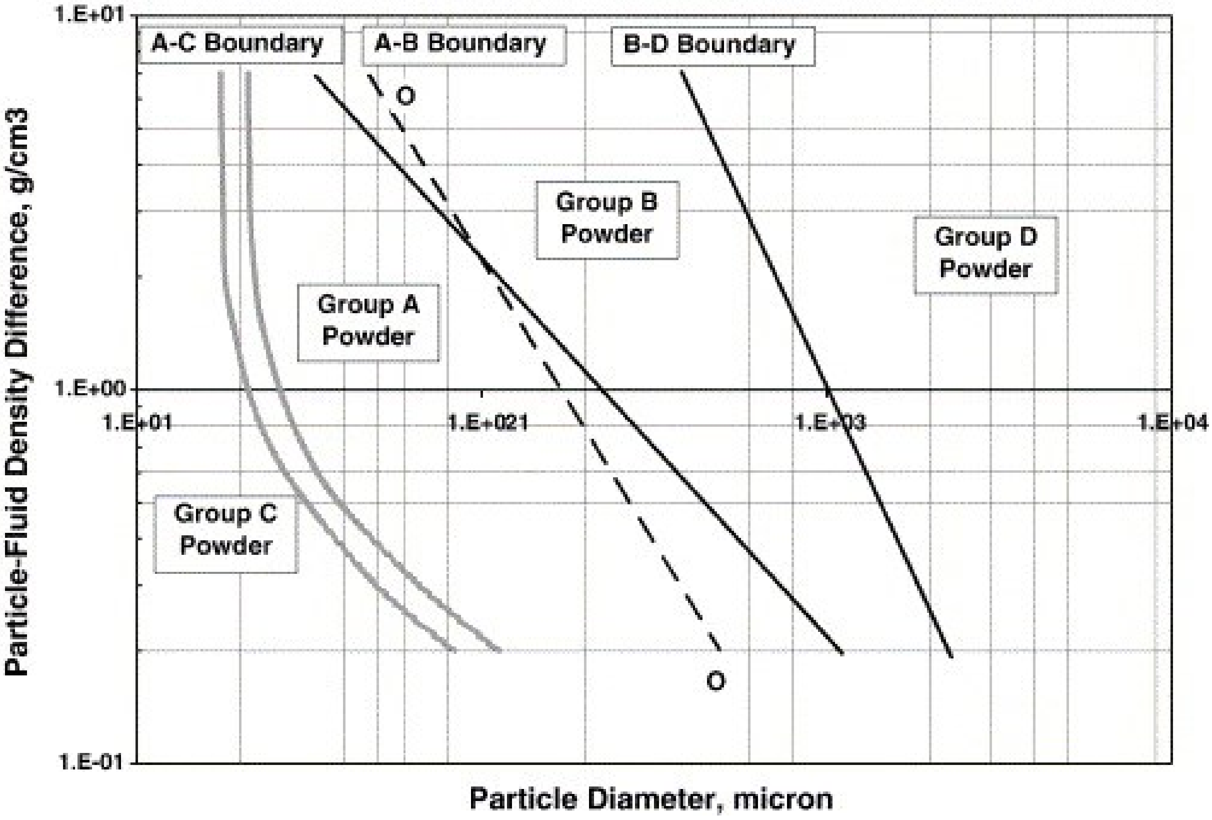

Figure 1.1 The original Geldart's classification of powders. Reproduced from [8].

This powder classification is now widely used as a model in all fields of power technology. Mainly, different bubble properties and minimum bubbling velocity were the parameters that established the boundaries between each group. Hence, fluidization properties can be predicted knowing from which group are the particles used, taking in account that with different temperatures and pressures than ambient a particle may appear in another group.

Not only bubbling features characterize the four different groups, a wide range of fluidization properties also change with particle group. A summary of the most important differences between groups can be seen in the following table [4]:

	Group C	Group A	Group B	Group D
Most obvious characteristic	Cohesive, difficult to fluidize	Ideal for fluidization. Exhibits range of non-bubbling fluidization	Starts bubbling at U_{mf}	Coarse solids
Typical solids	Flour, cement	Cracking catalyst	Building sand	Gravel, coffee beans
Bed expansion	Low	High	Moderate	Low
De-aeration rate	Initially fast, then exponential	Slow, linear	Fast	Fast
Bubble properties	No bubbles	Bubbles split and coalesce. Maximum bubble size	No limit to size	No limit to size
Solids mixing	Very low	High	Moderate	Low
Gas backmixing	Very low	High	Moderate	Low
Spouting	No	No	Only in shallow beds	Yes, even in deep beds

Table 1 Geldart's classification of powders group characteristics.

It is important to highlight the fact that the non-bubbling fluidization in group A is small, so bubbling fluidization systems are the most commonly used in industry for commercial use [4].

1.2 Multi-jet fluidized beds

Regarding the case of the study, the focus of this research is on fluidized beds with two vertical jets and the interaction between chimneys. This phenomenon remains uncertain since the amount of study behind it is limited. However, some research has been made about the interaction between chimneys and the correlation to some bed and particle parameters, apart from the creation of some models for the jet penetration height for a multiple-jet penetration case.

First, it is essential to define some terminology. Jet penetration height (H_j) is the length from the farthest point of the jet to the bottom of the bed, while multiple jet penetration height (L_j) is defined as the distance between the bottom of the bed and the point where two adjacent jets begin to coalescence together [9]. It is important to define the jet penetration height because most of the research regarding multi-jet fluidized beds focuses its studies on this parameter.

For a better understanding, the following figure clearly represents the difference between H_j and L_j:

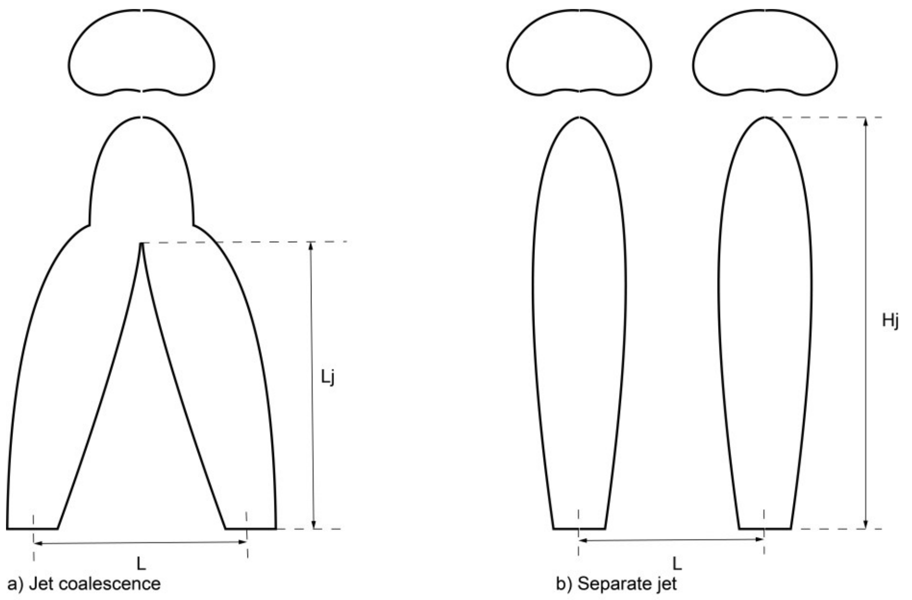

Figure 1.2 Schematic diagram of separate jet and jet coalescence for two jets with equal jet velocity.

Previous research claims that multiple-jet phenomenon can be classified in three different groups: isolated jets, transitional jets and interacting jets [9].

Isolated jets: when the distance between the jets is much greater than the nozzle width and the gas velocity is relatively low, both jets behave as independent single jets and do not interfere with each other.

Transitional jets: it is the transition zone between isolated and interacting jets. A moment in which the shape of the jets deforms due to interferences between each other, but they do not completely interact since they never meet.

Interacting jets: with enough jet velocity and small distance between nozzles, the two jets merge together.

Parameters influencing jet penetration height

Researchers have been studying the correlations between jet penetration height and a great number of parameters such as bed height, jet velocity, particle properties, gas properties, etc. However, only the ones taken in account in this study and considered important will be evaluated.

The jet velocity has the same result on jet penetration height for single and double jet systems. Jet penetration height increases with jet velocity until a point of relatively high jet velocities in which a plateau is reached [9].

Regarding the distance between nozzles L, it is directly proportional to the jet penetration height. Although more recent studies claim that the distance may be limited to a certain range, and in a non-isolated jet case, a variation in the distance between jets should also alter the flow behaviour and jet penetration [9]. These findings analysed the jet penetration height related to the nozzle distance-width ratio, $(L - d_j)/d_j$, with d_j as nozzle width, and came to the following conclusions:

In very large distances $(L - d_j)/d_j > 10$ the jet penetration height is not affected by separation between nozzles since the jets are behaving as isolated individual jets.

When the distance is intermediate $3.5 < (L - d_j)/d_j \leq 10$ the jets are behaving as transitional jets and the jet penetration height is inversely proportional to the distance between nozzles.

Lastly, in shorter distances $(L - d_j)/d_j \leq 3.5$ a situation of interacting jets is encountered and they both merge in a single greater jet in which jet penetration height transform into a parameter directly proportional to nozzle distance.

Experimental models have been developed to estimate the jet penetration height for single and multiple jet systems. Most of them, do not take in account the distance between nozzles, although as can be seen in the previous paragraph, it is an influential parameter, it is difficult to correlate to the jet penetration height since it changes its relationship with the nozzle distance depending on the jet interaction situation.

The relationship between nozzle distance and jet penetration height is still unexplained and wide different opinions exist about the topic. For instance, some papers claim that in a jet interacting case scenario, the jet penetration height is inversely proportional to the jet distance and it increases rapidly as the nozzles go near until it reaches a plateau from which the jet penetration height is now directly proportional to the nozzle distance, as it starts decreasing rapidly [9]. However, other study suggests that the jet penetration height is directly proportional to the nozzle distance and therefore, once the nozzles are interacting the jet penetration height will only reduce as they become nearer [10].

More recent studies with CFD simulations [2] have supported the correlations of [9] for isolated jets and [11] for interacting jets, that can be seen in Equations (3) and (4) respectively.

$$\frac{H_j}{d_j} = 26.47 Fr^{0.293} Re^{-0.1138} \tag{3}$$

$$\frac{L_j}{d_j} = 15.0 \left(\frac{\rho_f}{\rho_p - \rho_f} \frac{U_j^2}{g d_j} \right)^{0.187} \tag{4}$$

In which $Re = \rho_f U_j d_j / \mu$ is the Reynolds number near the jet nozzle, $Fr = \rho_f U_j^2 / \rho_p g d_j$ is the Froude number and g gravity. With U_j being the jet superficial velocity.

As commented before, it is clear that Equation (4) does not have a nozzle distance parameter in the correlation. Furthermore, the study that developed Equation (3) claims that when the two nozzles are very near, they can be treated as a single larger nozzle, with double the width of a single nozzle.

Flow pattern for interacting jets

The flow pattern given by the particle velocity for a single-jet system is different from the one obtained in a multi-jet system [12]. More recent research on a pseudo-2D fluidized bed established that the interaction between the spout channels perturbs the flow pattern: causing circulation of particles between the jets as well as on top of them and acceleration in the centre of the bed [3]. Using particle image velocimetry techniques (PIV), positron emission particle tracking (PEPT) and discrete particle modelling velocity simulations, the following figures can be used for a better understanding of the interaction between two jets:

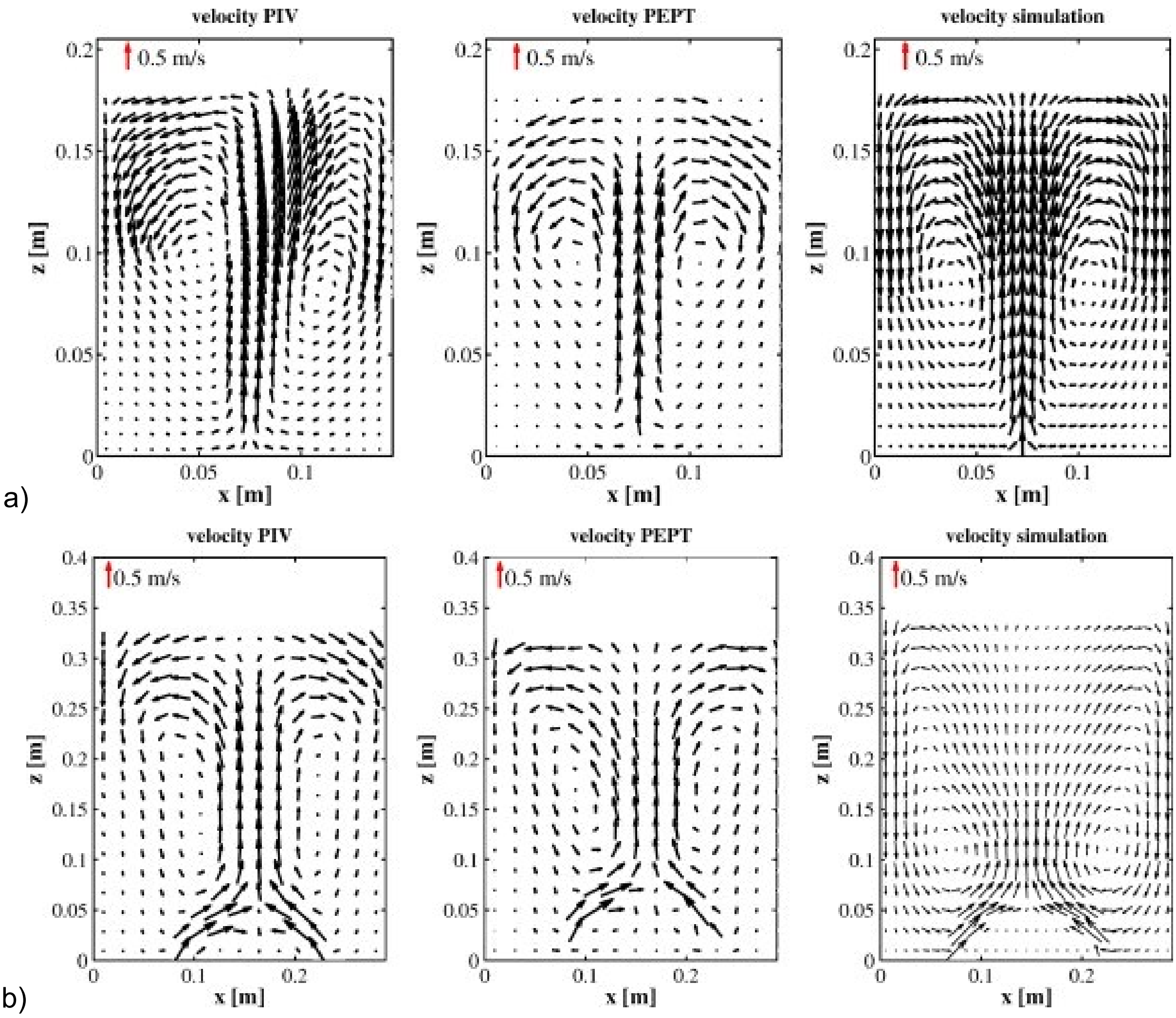

Figure 1.3 Flow velocity regime in a fluidized bed for a) single isolated jet and b) double jet interaction. Reproduced from [3].

2 EXPERIMENTAL METHODS

2.1 Experimental apparatus

The experiments were carried out in a rectangular fluidization rig with multiple rectangular slots. During the experiments the fluidization bed was filled with fine particles and two of the rectangular slots were used simultaneously for gas input, having the nozzle distance modularity of multiple slot combinations.

The experimental apparatus is formed of two transparent Perspex sheets for displaying purposes and an aluminium structure that forms a box for the fluidized bed of 0.45 m length, 0.45 m height and 0.04 m width. It has been proven that the presence of the walls will not affect the pressure distribution and by consequence, the fluid flow [13]. Moreover, the relatively big width of the bed in comparison with particle size will also prevent the panels of affecting the reliability of the results because it impedes the frictional forces to be transmitted to the centre of the bed [14]. A scheme of the apparatus can be seen in figure 2.1.

The bottom of the bed is constructed with twelve 35x5 mm slots separated 35 mm from each other and 50 mm separation for the ones in the centre which gives certain modularity in nozzle distance, with a fine metallic mesh over the slots to prevent small particles from falling off the bottom of the bed. Equating areas, an equivalent nozzle diameter can be found for this case scenario, resulting in $\sim 15\ mm$.

The chamber that forms the bed are sealed with injection rubber of 2 mm and some epoxy adhesive to consolidate the joints.

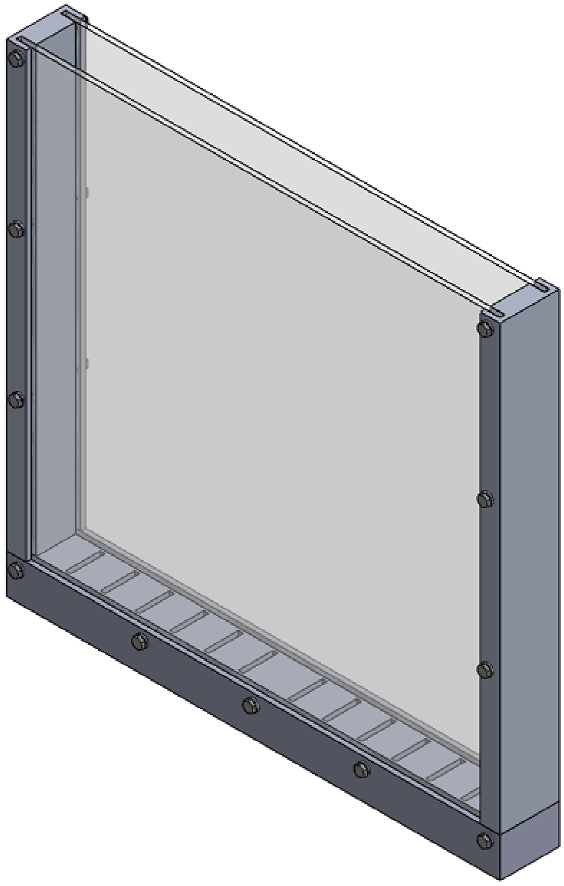

Figure 2.1 Schematic drawing of the experimental apparatus.

The operational method of the fluidized bed consists of two of the twelve slots working at the same time with air at $1\ bar$ and ambient temperatures of $\sim 20\ ℃$. The fluid flow of the nozzles comes from one single jet that is divided in two with the use of a tee connector. However, the use of a single air input comes with an aggravating issue: even though the bed height and particle properties are kept uniform alongside the bed and therefore, the pressure loss is supposed to be the same, a minimum change in the pressure loss between the two slots will make the gas only flow through one of them. As a solution, a pressure drop is generated in the tubes before the nozzle, using a packed bed of particles.

2.2 Particles

Experiments were carried using two different sets of particles, precisely, particles of types B and D in Geldart's classification of powders. Both set of particles will be glass beads of $2500\ kg/m^3$ and will be composed of spherical particles with sizes $250\text{-}415\ \mu m$ for type B and $600\text{-}800\ \mu m$ for type D. Summarized information about the particles used can be found in Table 2.

Designation	Material	Geldart type	d_p (μm)	$\rho_p\ (kg/m^3)$	$U_{mf}\ (m/s)$	Reference
Particles B	Glass	B	250-415	2500	~ 0.169	[15]
Particles D	Glass	D	600-800	2500	~ 0.352	[15]

Table 2 Characteristics of particles used and minimum fluidization velocity prediction.

The reason behind the particle choice relies in the fact that both types of particles are relatively large, which facilitates the data collection during the PIV process since the particles are coarser and the software can detect their movement easier.

2.3 Experimental measures

For measurements, PIV combined with a camera was used to characterize fluid flow patterns of the fluidized bed. Image processing software was used to analyse the drawings on tracing paper of the bed to estimate the area of particles that have been fluidized during the process.

Particle image velocimetry

PIV is an experimental non-intrusive technique that uses images captured at relatively low time spacing to obtain flow field data. The software used for this project was the open source Matlab module OpenPIV, that estimates velocity fields from images of particles and its post-processing functions also cover vorticity, rate-of-strain, dissipation and Reynolds stresses [16].

For the experiments, a high-resolution camera recorded the region of interest in the fluidization process with 240 fps at 720p quality. It was important to have a uniform and bright illumination of the grid for a better video recording. These videos were converted in a series of images that later were analysed with the software named before and the flow patterns and particle velocities can be obtained.

Since the flow pattern remains fairly constant once the bed is fluidized, only a few seconds of video were taken for each case, so the weight of the image data is reduced and consequently, the processing time taken by the software will be reduced too. OpenPIV proceeded throughout all the images and a flow pattern was obtained, some tools in this software can establish a scale based on the number of pixels, with such scale, the program was able to also calculate the particle velocity.

Image processing

The software used for image processing was ImageJ2, an analysis program with extended use in science applications for image processing [17].

This program analysed the sketches taken of the bed in order to obtain the amount of particles fluidized. First, after the bed has been fluidized, the gas flow can be stopped, and the bed comes to a static packed state again. At that moment, a drawing of the bed was made from tracing paper for later processing in ImageJ2. This software possesses a tool that allows the user to establish a numeric scale based on the number of pixels, and once the scale is implemented, the areas of the different regions of the bed can be calculated.

Tracing drawings of the bed that relate to its fluidized state are possible because once the bed has been fluidized and comes back to a packed bed, particles that have been moving during the process (fluidized) and the ones that did not (non-fluidized) form clear distinct zones. These zones are usually separated by a narrow line of particles that have been moving from the top to the bottom of the bed due to friction, and therefore, they form another pattern.

2.4 Numerical models

A great number of numerical models have been built to predict jet penetration height in single and multiple jet systems. However, these models predict data within wide ranges of error (usually around $30\sim40\%$) and, not taking in account all the parameters that have an impact on jet penetration height, as it is distance between nozzles.

Also, it is important to highlight the fact that these correlations for the jet penetration height do not consider all the parameters, and even less, the one that is scope in this study, the distance between nozzles. Furthermore, the inconsistency of the results between the models is very clear, as some contradict each other in the effect of nozzle distance and jet velocity for instance, and they were developed for very particular case scenarios of particle type, jet velocity, bed shape and dimensions, separation between nozzles, etc. and the models are completely inconsequential in other situations.

Below, can be found the models that were used as a comparison with experimental data and are a summary for some of the previous work concerning this topic.

Basov et al., 1969 [18] developed a correlation for the jet penetration height that can be used in single and multiple jet systems:

$$\frac{L_j}{d_j} = \frac{0.919 d_p}{0.0007 + 0.566 d_p} \frac{U_j^{0.35}}{d_j^{0.3}} \tag{5}$$

where d_p is the particle mean diameter.

Yang and Keairns, 1979 [11] developed a correlation with the available data on jet penetration in multiple jet systems and with the two-phase Froude number:

$$\frac{L_j}{d_j} = 15.0 \left(\frac{\rho_f}{\rho_p - \rho_f} \frac{U_j^2}{g d_j} \right)^{0.187} \tag{6}$$

Wu and Whiting, 1987 [19] estimated the jet penetration height for a multiple jet system as a function of particle and fluid density, nozzle width and separation:

$$L_j = 8.79 \left(\frac{\rho_p d_p}{\rho_f d_j} \right)^{-0.236} \left(\frac{L - d_j}{2} \right) \tag{7}$$

Blake et al., 1990 [20] constructed an equation to correlate the jet penetration height for multiple jet systems based on experimental data:

$$\frac{L_j}{d_j} = 55.6 \left(\frac{U_j^2}{g d_j} \right)^{0.251} \left(\frac{\rho_f}{\rho_p} \right)^{0.322} \left(\frac{\rho_p U_j d_p^2}{\mu_f d_j} \right)^{-0.134} \tag{8}$$

where μ_f is the dynamic viscosity of the fluidization fluid.

Luo et al., 1997 [21] suggested a correlation for the jet penetration height of two vertical jets with the Stokes and Froude number:

$$\frac{L_j}{d_j} = 55.6 Fr^{0.31} St^{-0.15} \tag{9}$$

Yates et al., 1995 [22] studied the bubble coalescence and constructed a correlation for the average coalescence height for multiple jets:

$$\frac{L_j}{H_{mf}} = 0.57 \left(\frac{L}{d_j} \right) \left(\frac{U_j}{U_{mf}} \right)^{-\frac{1}{3}} \tag{10}$$

Hong et al., 2003 [9] proposed a correcting factor for interacting jets for the Equation (4), also developed in the same paper:

$$\frac{L_j}{d_j} = 26.47 Fr^{0.293} Re^{-0.1138} \times \alpha \tag{11}$$

where

$$\alpha \cong \begin{cases} 1.4 \sim 1.6, & 0.0 \le L \le L_c \\ 1.0, & L > L_c \end{cases} \tag{12}$$

and L_c is the critical distance between jets, considered as the minimum distance in which jets start interacting with one another and can be calculated with the following correlation:

$$L_c = d_j + 2 \times H_j \times \tan\theta \tag{13}$$

where

$$\tan\theta = \frac{1}{10.4}\left(\frac{\rho_s d_p}{\rho_g d_j}\right)^{0.3} \tag{14}$$

Also, the same equation can be used to calculate jet penetration height for interacting jets using a nozzle of double the width when they are very near, since they can be treated as a single larger nozzle as stated in some sections before.

Lastly, Guo et al., 2000 [10] proposed the following correlation based in experimental data:

$$\frac{L_j}{H_{mf}} = 0.6056\left(\frac{U}{U_{mf}}\right)^{-0.3284}\left(\frac{L}{d_j}\right)^{0.1085} \tag{15}$$

where H_{mf} is the height of the bed at minimum fluidization velocity.

As can be seen in the correlations commented before, most of the models do not take in account the nozzle distance. Also, the discrepancies between models and their inaccuracy is clearly present, giving results for a same set of variables with great differences in value.

Using Equations (3), (13) and (14) the critical distance at which the jets of the experimental tank would start interacting can be obtained for particles B and D respectively:

$$Particles\ B: L_c = 68.47\ mm\ \rightarrow (L_c - d_j)/d_j = 3.56 \tag{16}$$

$$Particles\ D: L_c = 57.80\ mm\ \rightarrow (L_c - d_j)/d_j = 2.85 \tag{17}$$

Knowing that the critical distance for the experimental tank can be predicted. The jets will start interacting at a distance of $\sim 70\text{-}60\ mm$, which does not allow many possible combinations in the tank slots, considering that the separation between the ones in the middle is $50\ mm$. However, since these correlations are experimental, an equivalent diameter is being used and based on previous studies on jet interaction with rectangular slot beds, it is expected that the results vary significantly in terms of the threshold for jet interaction.

For instance, recent experiments on multi-spout fluidized beds, accomplished jet interaction with distance between nozzles completely different at the ones that Equation (13) suggests in a rectangular slot fluidized bed: achieving jet interaction at a distance of $140\ mm$ while the calculated critical distance would suggest $L_c = 68.30\ mm$ for the case [3].

3 RESULTS

The lab workload consisted of a set of experiments with the particles type D and B characterized before and with an air supply at $1\ bar$ and room temperature $\sim 20\ ℃$. The variables to take in account were jet velocity and distance between nozzles, which were varied between each experiment. A high-speed video and a drawing of the bed was taken in each case for the later analysis with the experimental methods mentioned.

Though the two types of particles were from different groups of Geldart's classification, both set particles gave similar results regarding the fluidization behaviour, fluid flow, flow regime, etc.

Every experiment was performed several times to ensure the reliability of the results. Regarding the experiments of the area fluidized, the high-resolution scans giving suitable meter-pixel scales and the use of an image processing program contributed to very accurate results. Same occurred with the PIV results on jet interaction and jet penetration height: having video recordings of 240fps and 720p resolution also resulted in very fine time and space scales. However, the measures on-site of the jet penetration height were more complicated since the jet penetration height is a fluctuating parameter that makes the validation of the data and taking the measure itself very problematic. Therefore, multiple samples of the same experiment were taken and the resulting average was the one used for this section.

3.1 Area fluidized

First, it was studied the area of particles fluidized in the bed according to the variation of nozzle distance keeping the jet velocity constant and the area fluidized for a single nozzle with a varying jet velocity. It was assumed that two jets interacting have a similar behaviour in respect to the area fluidized to one isolated jet when only the jet velocity is varying.

Influence of nozzle distance

The experiments performed in both sets of particles point out that the area of particles fluidized does not vary with nozzle distance. It is logic to think that as two interacting jets very near from each other can be interpreted as a single jet with double the nozzle width, it will fluidize the same area of particles as two separate jets.

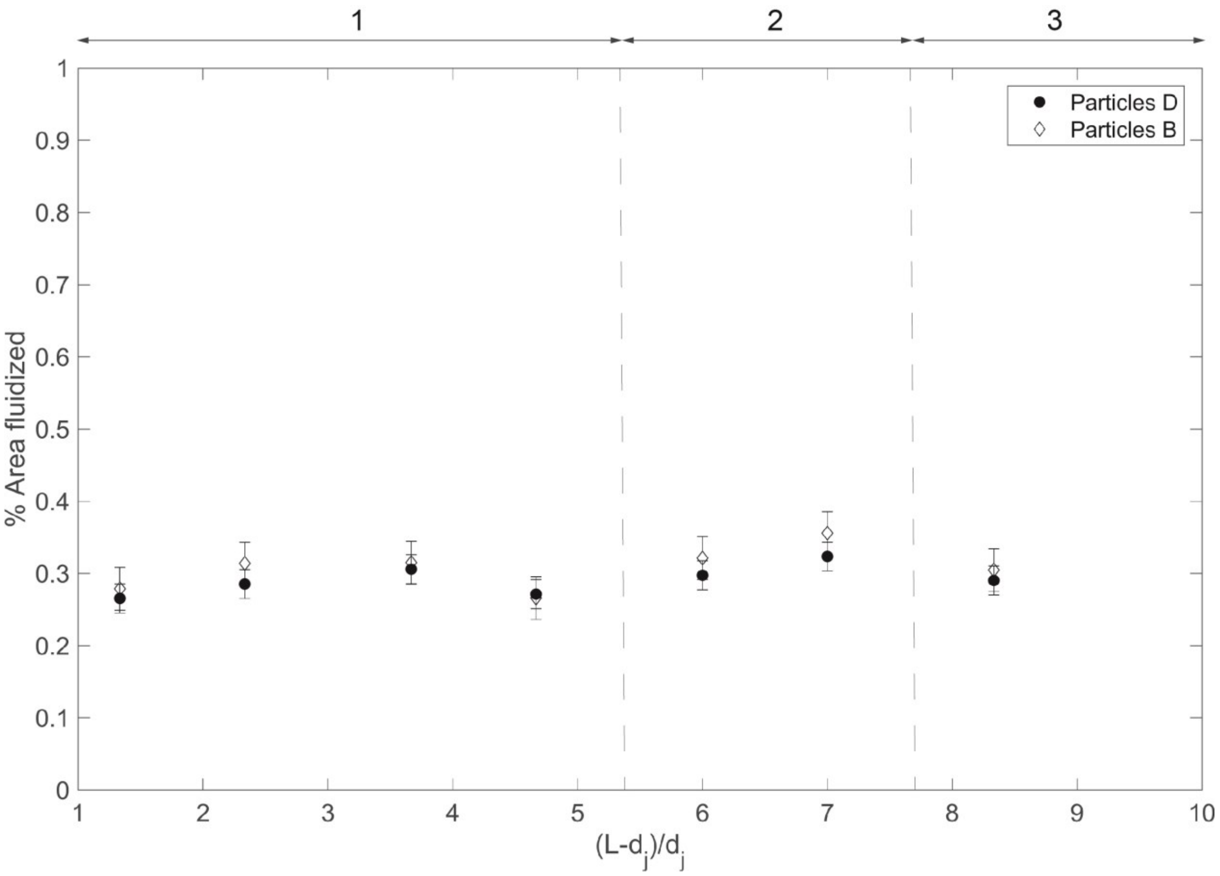

Figure 3.1 Scatter of the results in percentage of area fluidized depending on nozzle distance for both sets of particles indicating regime zones for 1) interacting jets, 2) transitional jets and 3) isolated jets.

As can be seen in Figure 3.1, the distance between nozzle does not appear to have a significant influence on the area fluidized since the highest difference between values does not differ from more than 10%.

Influence of jet velocity

Now, knowing that the nozzle distance does not influence the amount of particles fluidized, the assumption made about the reliability of proceeding with the experiment with one single jet and discretizing the jet velocity as the only variable has been proven to be an appropriate approach.

The experiments executed gave as a result a relation between jet velocities and area fluidized. It appears that the fluidized area increases slightly with the jet velocity, and although the increments are relatively low, the points tend to a linear shape relation between jet velocity and area fluidized.

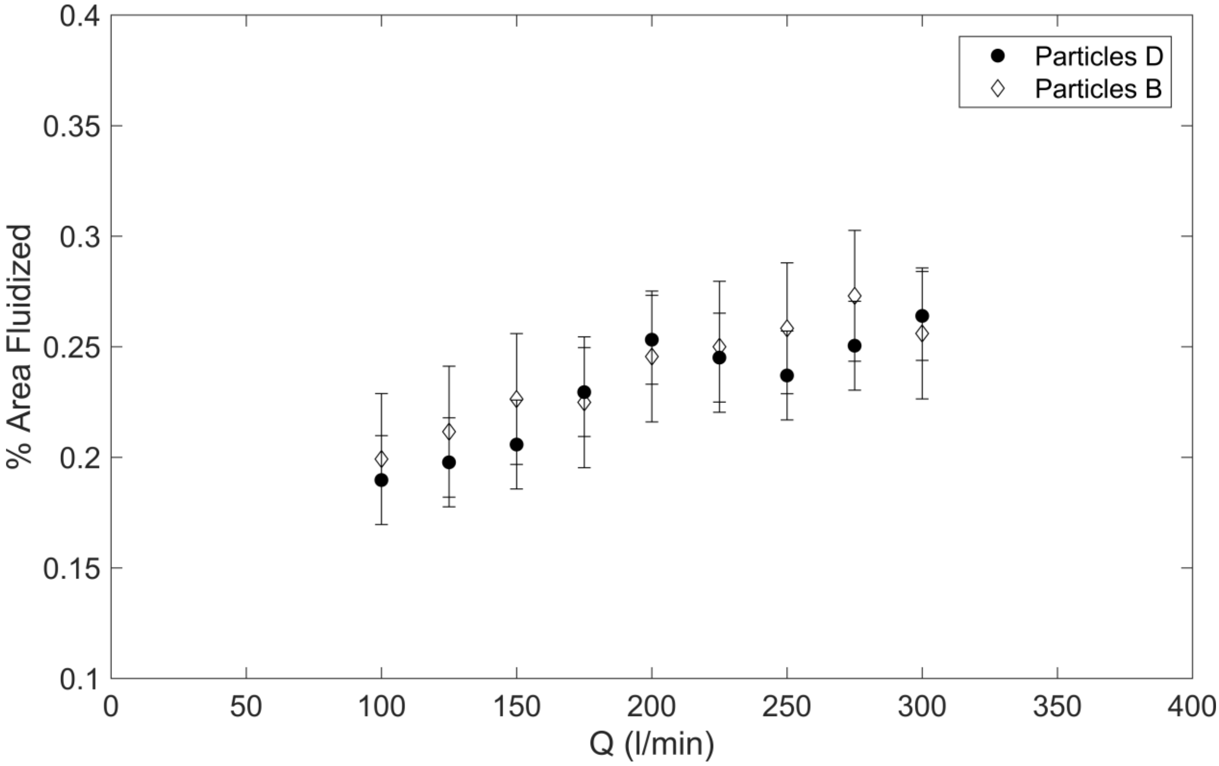

Figure 3.2 Scatter of the results in percentage of area fluidized depending on jet gas flow-rate for both sets of particles.

However, the shape of the bed also experiences an interesting change of shape, as can be seen in Figure 3.3, as the jet velocity increases, the top of the bed at the axis of the jet decreases its height and the bed expands to the sides.

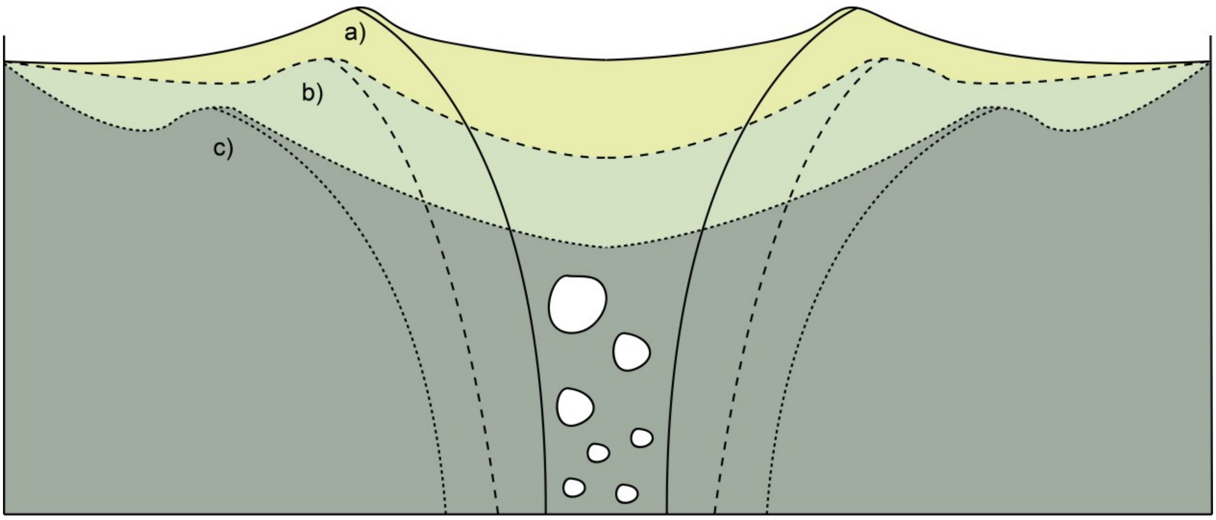

Figure 3.3 Sketch of the bed fluidized by a single fixed width nozzle at a) low gas velocities, b) medium gas velocities, c) high gas velocities.

These changes in the shape of the bed for a fixed nozzle width are due to the fact that once the bed is fluidized ($U > U_{mf}$), an increase on the jet velocity involves an increase in the spouting of the fluidized particles, therefore the height at the centre of the nozzle reduces as more particles are deposited onto the sides.

Overlooking the shrinking of the top of the bed, seems to be a clear correlation between the width of the bubbling fluidized region and the gas velocity. However, the data collected in Figure 3.2 may not be completely accurate because it seems that as the bubbling fluidized region increases its width with jet velocity, the friction governed regions also tend to be wider as they become less steep. To be clearer, these friction governed regions (see in Figure 3.4) are fine lines that separate the fluidized zone from the non-fluidized and are formed by moving particles from the top of the bed to the bottom because of gravity and governed by the friction between them, hence, they cannot be considered fluidized. As the fluidized area becomes wider, these fine (initially close to vertical) lines tend to be less steep which leads to higher angles of friction between particles within these areas and therefore, an increase in size as more particles tend to lay on these areas due to the increase of the frictional forces.

Also, it is important to be considered that the area will reach a plateau eventually, as it will have a limit when the upper part of the fluidized region is as wide as the walls of the fluidization apparatus.

3.2 Jet interaction

For the jet interaction, a constant flow-rate throughout all the experiments was used, and the distance between nozzles was varied for both sets of particles studying the flow regime for each case scenario.

Both particles appeared to have a threshold at $(L - d_j)/d_j = 4.67$ at which they would start interacting, which is a nozzle distance of $85\ mm$. Seems that the value of the critical distance is different from the one expected by Equation (13).

Change of flow regime

At $(L - d_j)/d_j = 4.67$ the jets start interacting with each other, producing a significant change of the flow regime in the bed. The case directly before that both jets are in a transitional situation, in which they are not interacting, but their flow patterns are being affected and deformed by each other.

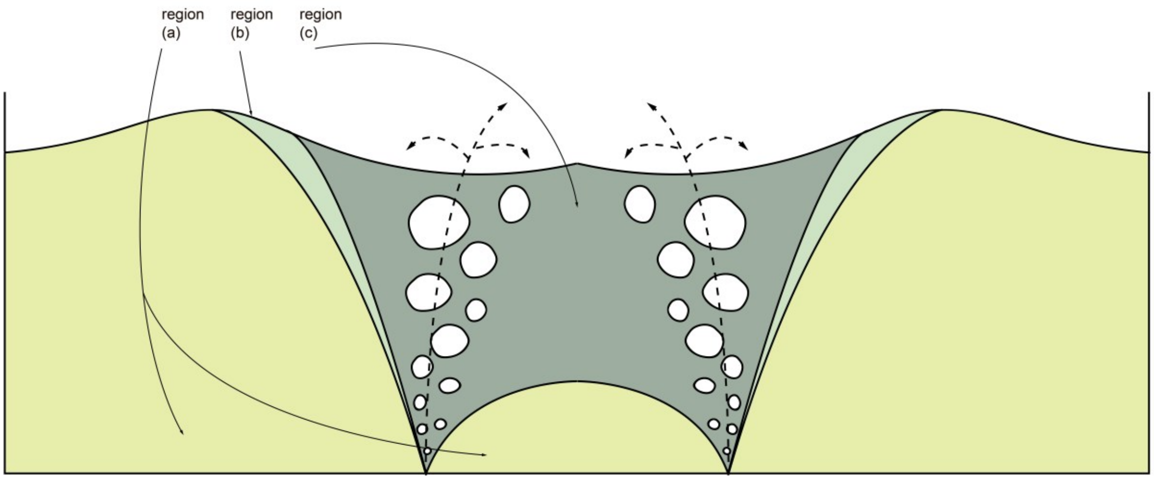

Figure 3.4 Sketch of fluidized bed at $(L - d_j)/d_j = 6$ with transitional jets, separating zones a) static non-fluidized region, b) friction governed region and c) fluidized region.

As can be seen Figure 3.4, the fluid flow of the individual jets is being distorted by the effect of each other and they tend to orientate towards one another. In the bed three different zones can be identified: a non-fluidized region; a friction governed region, that was commented earlier in which particles are moving due to friction from top to the bottom of the bed, but they are not fluidized; and a fluidized region, with a bubbling fluidized channel in the middle and some non-bubbling fluidization on the sides.

The non-fluidized region that exists between the jets will be referred as dead-zone, this particular region of the non-fluidized area exists between jets that are not interacting, and the height depends, to some extent, on the grade of interaction in which they stand. For instance, when both jets are far from each other the dead-zone has a relatively great height, being as high as the bed fore very separate jets; as nozzles come closer, the dead-zone height decreases until disappears with jet interaction behaviour.

It is important not to confuse the variability of dead-zones with jet interaction, as for isolated jets this zone usually reaches the top of the bed and in some cases the reduction of its height is purely because of geometric reasons, for instance, when the fluidization zones of the two jets coincide at the middle with no actual jet channel interaction.

When the jets start interacting, the fluid flow of both jets is distorted towards one another as in transitional jets, but in an interacting situation, both fluid flows converge in the centre resulting in a single larger jet towards the top of the bed.

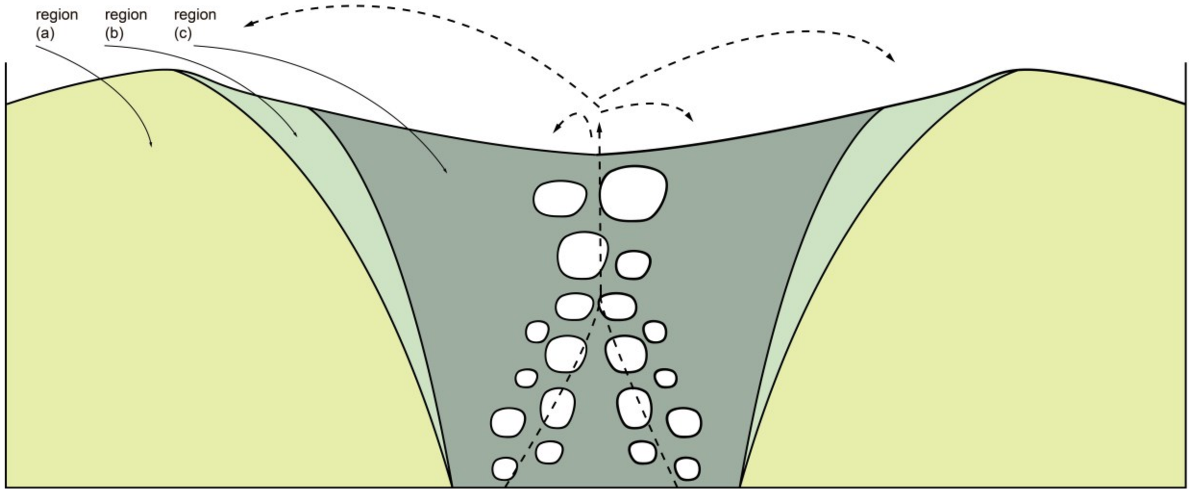

Figure 3.5 Sketch of fluidized bed at $(L-d_j)/d_j = 4.67$ with interacting jets, separating zones a) static non-fluidized region, b) friction governed region and c) fluidized region.

Regarding the flow velocity field, a comparison between $(L-d_j)/d_j = 6$ and $(L-d_j)/d_j = 4.67$ can be seen in Figure 3.6, that is the result of the particle image velocimetry of both case scenarios.

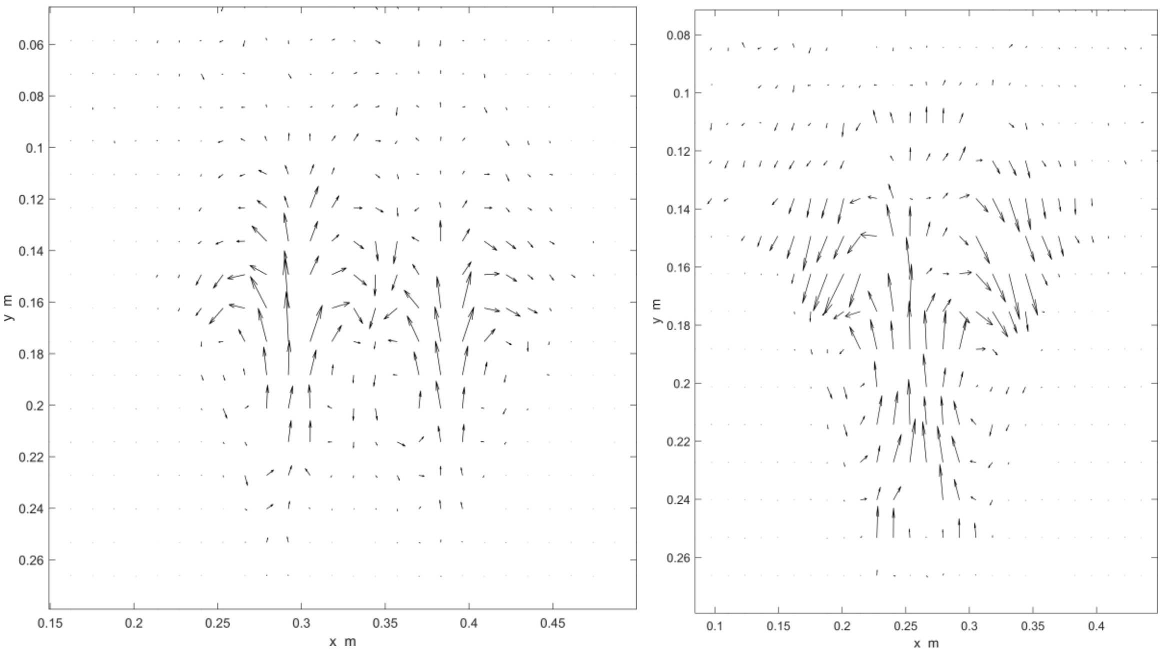

Figure 3.6 PIV flow velocity field comparison between $(L-d_j)/d_j = 6$ as no interacting jets (left) and $(L-d_j)/d_j = 4.67$ as interacting jets (right).

It is clear the coalescence of the jets in the graph of flow velocity field, and it can certainly be seen how both jets tend to approximate to each other till they converge in one bigger single yet. Also, given the PIV results, seems that the flow velocity between the two interacting jets at the bottom of the bed is not significant compared to the rest of velocities of the flow field, however, the dead-zone between jets in the interacting case scenario has disappeared completely because the particles have been fluidized.

During the experiments, intermittent large bubble formation appeared on the bottom of the bed between the nozzles, which may be the reason behind the disappearance of the dead-zone even though the fluid velocity between the nozzles seems to be insignificant. As can be seen in Figure 3.7, while the two jets were having an ordinary behaviour, arbitrary large bubbles formed at the bottom of the bed due to the coalescence of bubbles from the two jets. Phenomenon which led to movement of the particles between jets at heights lower than L_j and a more violent spouting.

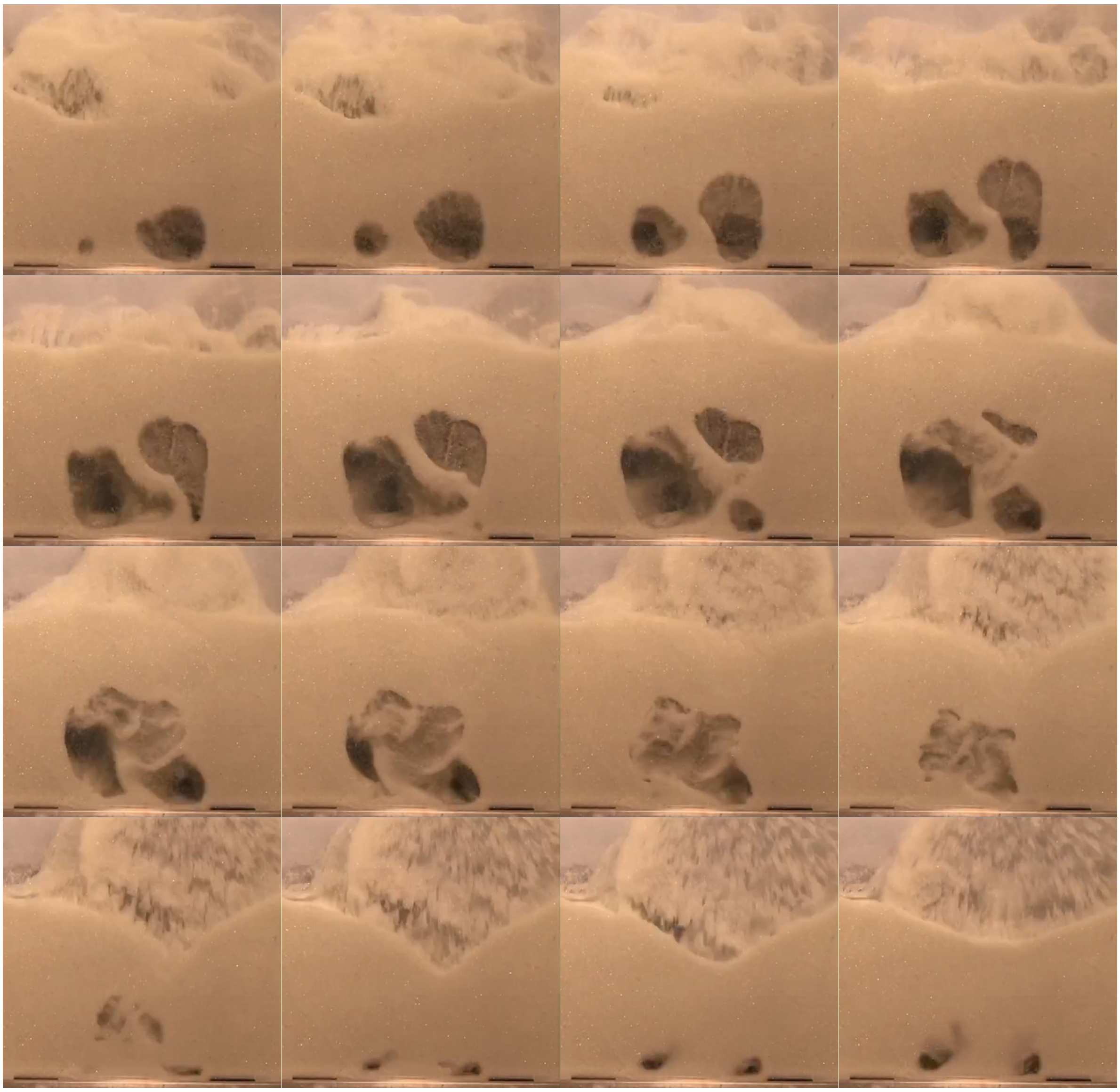

Figure 3.7 Transition from $t = 0\,s$ s to $t = 0.25\,s$ of singular large bubble formation due to fluctuations in jet interaction at $(L - d_j)/d_j = 3.67$.

Furthermore, concerning other aspects in the flow regime transition, the bubbling fluidized region becomes wider, which contributes to a more agitated fluidization and more spouting of the particles at the top of the bed.

Jet penetration height

For the jet penetration height, the experiments were performed from the threshold found at $(L - d_j)/d_j = 4.67$ and a measure was taken for the jet penetration height from the tank itself and from the PIV results of the flow velocity field.

It has been found that the jet penetration height, at constant gas flow rate, is directly proportional to the distance between nozzles in a jet interacting situation. Hence, as the nozzle become nearer, the jet penetration height decreases until the distance between nozzles is zero (effectively one nozzle) and the jet penetration height for interacting jets would be zero.

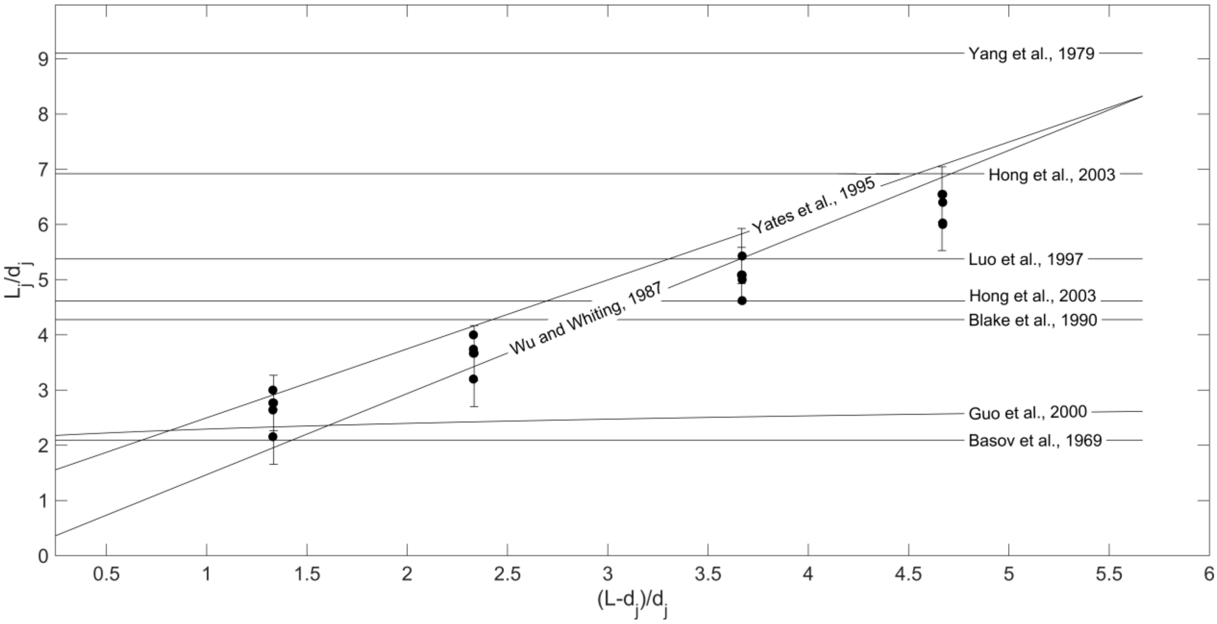

Figure 3.7 Representation of the prediction of jet penetration height in multi-jet systems by different models with the experimental data obtained with on-site and PIV measures at a constant flow rate.

As expected, the models which do not consider the distance between nozzles for the correlation of the jet penetration height give results completely different with the experimental data obtained. While the models of Yates et al., 1995 and Wu and Whiting, 1987 result in curves closer with the jet penetration height obtained in the experiments.

The correlation of Guo et al., 2000, does take in account the distance between nozzles, however, the effect that this variable has on the jet penetration height is completely insignificant in comparison to the other models and the data collected.

Focusing on the correlations that produced more accurate results regarding the experimental data (Yates et al., 1995 and Wu and Whiting, 1987), both models are particle type dependent, because they take in account particle size and minimum fluidization velocity as can be seen in Equations (7) and (10). However, the curves represented in Figure 3.7 did only consider one type of the particles because the difference in value was not significant enough since the purpose of the graph is offering an initial perspective on how the data obtained correlates with the different models. Knowing that, a second more detailed plot for the correlations of Yates et al., 1995 and Wu and Whiting, 1987 can be seen in Figure 3.8 considering particle type.

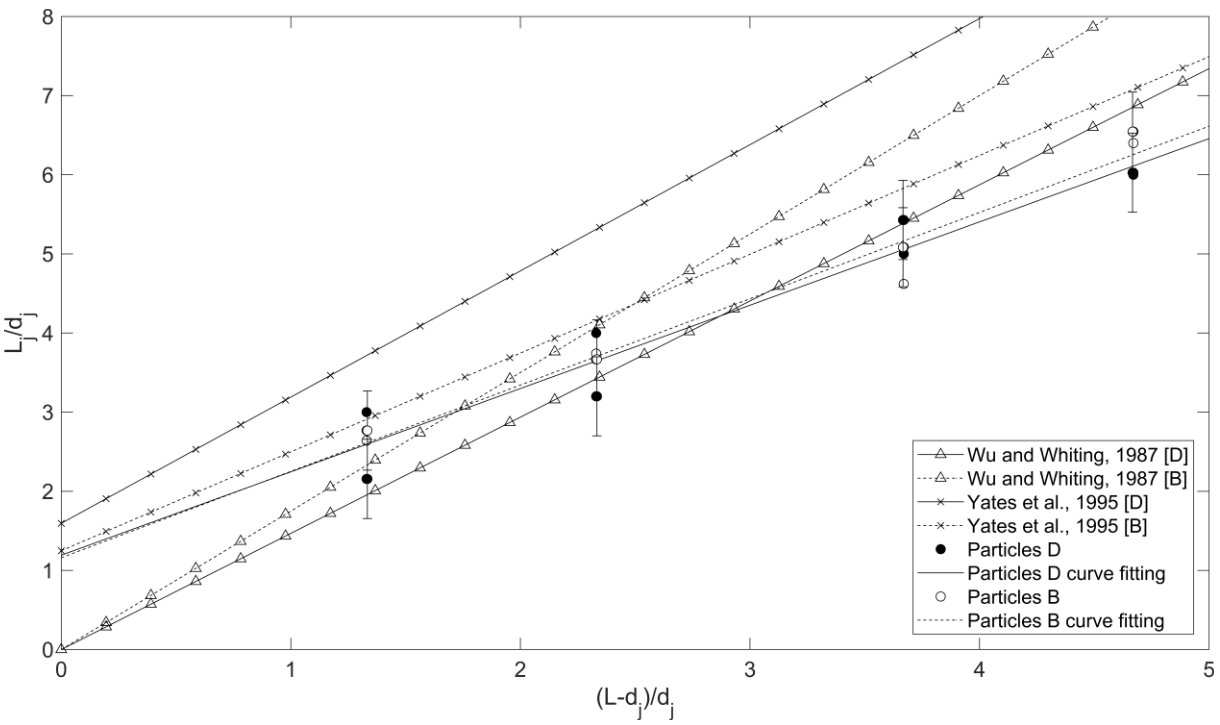

Figure 3.8 Representation of the prediction of jet penetration height in multi-jet systems given by the correlations of Yates et al., 1995 and Wu and Whiting, 1987 with the experimental data obtained with on-site and PIV measures at a constant flow rate for particles type B and D.

Seems that the correlation of Wu and Whiting, 1987 for particles type D is the best fitting one for the experimental data collected as Yates et al., 1995 for the case of particles B. However, the experimental data was performed with constant jet velocity, hence, the accuracy of the models when the jet velocity is also a variable are unknown. Nevertheless, this issue happens with every jet penetration model, the accuracy of the results is very dependent on which variables are being considered, although most of them seem to focus on the relation with the jet velocity.

DISCUSSION

This study on the interaction between nozzles for a fluidized bed has been focused in the effect of nozzle distance and jet velocity correlations for the area of particles fluidized and the correlations between nozzle distance and jet penetration height.

The reliability of jet interaction at the threshold $(L - d_j)/d_j = 4.67$ has been proven with PIV and on-site drawings of the bed that show the convergence between the nozzles into a single larger one and the disappearance of dead-zones of unfluidized particles between jets.

Regarding the study on the areas, the drawings converged in appropriate results for the area fluidized on nozzle distance. However, the changes of shape in the bed, and the enlargement of the friction governed regions that involve an increase in the jet velocity, may have altered the reliability of the results on the correlations of area fluidized with jet velocity, since the drawings are not as effective in the identification of those regions when they are not a fine line of particles.

On the other hand, the similarities between the on-site measurements on jet penetration height and the PIV results show that the data collected is valid. Even though, is important to highlight that the fluctuations of a running fluidized bed make the data collection of jet penetration height problematic and even inaccurate at times.

Furthermore, the use of PIV for the validation of the results and the verification of jet interaction was a very favourable decision, even though, it also presents its issues not being able to track very fine particles and the spouting of the particles affecting the flow velocity fields at some scenarios.

Some error bars can be seen in the figures of the results section, every point has an error bar that represents a confidence limit of 95%, except for the points regarding PIV results, since the PIV method obtains the velocity field from an average of its own results, and there was no variation on the value between the samples.

CONCLUSIONS

Conclusions

The effect of the coalescence of vertical jets was studied experimentally in a gas-solid fluidized bed, for the parameters of amount of area fluidized and jet penetration height.

Regarding the amount of area fluidized, the nozzle distance does not correlate with the amount of particles fluidized. Hence, if the area fluidized is the same for two vertical isolated jets and for interacting jets, it is valid to think that when two jets converge with each other they form a single larger jet of double the size. On the other hand, the jet velocity seems to have an effect on the amount of particles fluidized and shape of the area fluidized: as jet velocity increases, the top of the bed shrinks and it becomes larger to the sides, fluidizing more area of particles; having a maximum when it reaches the walls of the bed.

The jet coalescence has been proven to happen at $(L - d_j)/d_j = 4.67$ for the specific case studied. Finding that disputes the certainty of the critical distance that suggests Hong et al., 2003 with Equation (13), which also relates with the fact that the correlations on jet penetration height from which the Equation (13) was constructed also resulted in values very different from the experimental data obtained in this study.

Moreover, it was found an inconsistency between the bed sketches and the PIV results, seems that even with insignificant jet velocities between nozzles at the bottom of the bed in an interacting jet situation, the dead-zones completely disappeared because the particles forming these zones were fluidized; seems that the reason could be the intermittent formation of large bubbles at heights smaller than L_j that move the particles in that region.

Lastly, the jet penetration height for interacting jets studied in the experiment was plotted against a great number of numerical models. The inconsistency of these models is present by the great deviations between numerical results and experimental data, mainly in models which do not take into consideration distance between jets. Also, it was found that the correlations of Yates et al., 1995 and Wu and Whiting, 1987 on the jet penetration height of multiple jet systems for particles type B and D, respectively, and constant flow rate, delivered very sensible results in comparison with the experimental data.

Recommendations

The use of PIV is very recommended as the tools offered by the technology are essential for the validation and verification of results in fluidization procedures. Furthermore, in the case of jet penetration height, being able to obtain the flow rate from a high-speed video recording facilitates the collection of data. However, it is important to consider that very fine particles and a lot of spouting is very negative for the accuracy of results.

A proper design of the experimental rig is also vital. Modularity in the distance between slots is very important, an improvement in modularity can be achieved by using different distances between slots instead of opting for a symmetrical and organized distribution, which will help the data collection as more possible distances (by means of combination) between jets can be studied, sadly, that was not the case of the experimental tank in this study and the modularity was limited. On the other hand, if the nozzles are fed by one single supply, it is crucial to reduce the fluctuations so all the nozzles have the same jet velocity.

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