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EFFECT OF THE GEOMETRY OF A GAS DISTRIBUTOR (TUYERE TYPE) ON FLUIDIZATION OF A BINARY MIXTURE BIOMASS-SAND

Daniel Portioli Sampaio
Patrícia Gomide Ferreira
Araí Augusta Bernárdez Pécora*
University of Campinas, School of Mechanical Engineering
R. Mendeleyev, 200, 13083-860 - Campinas, SP, Brazil
daniel.portioli@gmail.com, arai@fem.unicamp.br

Abstract. *Fluidization systems involving biomass to produce energy, such as pyrolysis, gasification or combustion reactors, require well-mixed granular material inside the fluidized bed in order to increase processes efficiency. In these systems, the gas distributor design is an important factor to assure the fluidization quality. Reactors typically use sand as inert material, whose density and size may differ substantially from typical biomass sources. This paper presents an experimental study of multi-tuyere gas distributors using sugarcane bagasse as biomass and sand as bed material inside a column with 0.10m diameter and 4m height. The binary mixture studied was composed by 5 wt% of biomass which is a typical composition in combustors, gasifiers or pyrolysis reactors. Tests were performed at room temperature and pressure. Different geometrical parameters of the tuyere gas distributor were analyzed: (i) number of orifices, (ii) orifices diameter, (iii) angle of the gas jet in the vertical direction, and (iv) alignment angle (angle between the orifice and the tangent of the circle involving the tuyeres). In order to verify the influence of the geometric parameters on the quality of fluidization a statistical analysis was adopted. The bed pressure drop as a function of the gas velocity was measured for each operational condition and the mixture quality was verified applying a frozen bed methodology. Samples of the bed material were collected at different heights and radial positions in order to obtain the mixture density and comparison with the density of the ideal well-mixed bed. The obtained results showed that only two of tested parameters were statistically significant: number and diameter of orifices. These results can be useful for design engineers involved with energy generation from biomass in fluidized bed reactors.*

Keywords: *Bubbling fluidized bed, design distributors, segregation, binary mixture of sugar cane bagasse and sand.*

1. INTRODUCTION

Nowadays, the demand for power generation processes presenting high conversion efficiency and low pollutant emissions is increasing. In this scenario new developments regarding fluidized bed technology could help by improving the contact between gas and fuel. In Brazil, there are many sugar mills to produce ethanol that generate a large amount of bagasse as a residue. This waste material would become a good solution for energy cogeneration applying the fluidized bed technology (Geris, *et al*., 2011). Despite the large amount of bagasse produced in Brazil (145.5 million tons), only small amounts have been used as energy marketed (PDE-2021, 2013). For this reason, the use of sugarcane bagasse as a biomass becomes potential to increase and diversify the renewable sources in the national energy matrix. This fact is interesting for Brazilian government and was the motivation for the development this work.

One important component of the fluidized systems is the gas distributor, since it directly affected by the dynamic behavior of the fluidized bed. This influence can be seen in the initial bubble size and direction of the gas jets through the bed. Therefore, the function of the gas distributor is to assure an effective and uniform distribution of the incoming gas through the solid particles. Several types of gas distributors have been designed in order to improve the operating conditions in fluidization processes (Wormsbecker, *et al.,* 2007). Also, Basu (2006) and Geris *et al*. (2011), described that the distributor presents itself as one of the key component for achieving an efficient solid fuel reaction in thermal process (like gasification, pyrolysis and combustion). It is for this reason that an inhomogeneous distribution results in numerous problems, such as the collapse of the gasifier due to agglomeration in the bed, erosion and segregation. Regarding fluidized bed reactors working with biomass, the beds are usually composed by an inert material (sand or ashes), which presents different size and density of the biomass particles. Wormsbecker, *et al*. (2007) reported that several models of gas distributors have been designed in order to improve the operating conditions in various fluidization processes and to increase the rate of mass and heat transfer of non-reactive and reactive processes. Additionally, Zhu *et al*. (2011) showed that the gas distributor design affect the entire distribution of solids over circulating fluidized beds.

The upward flow of bubbles plays an important role in driving and movement of the particles and thus has a significant impact on the mixing process inside the bed. The initial bubble size is dependent on the type of distributor used (Dong *et al*., 2009). In addition, regarding bubbling fluidized beds, a poor fluidization can result in a low bed pressure drop, resulting in a non desired or poor fluidization with some regions temporarily suspended and regions where intermittent preferential channels for the gas stream can be observed (Guo *et al*., 2005). Generally, to ensure stable operation, the pressure drop across the distributor must be up enough, so that the flow through the gas distributor is not disturbed by the pressure fluctuations in the bed (Guo *et al*., 2005).

However, the minimum fluidizing velocity (U_{mf}) is another very important parameter for the analysis and design of fluidized beds. It not only defines the lower limit in which the fluidization occurs, but it is also an usual parameter in the modeling process of fluidized beds (Hilal *et al*., 2001).

Nevertheless, regarding fluidization of binary mixtures, the bed is composed by particles presenting different size and/or density, thus one specie will fluidize at lower gas velocity than the other. As a consequence, a separation among the different particles is observed. The larger and/or heavier particles present the tendency of sinking and the smaller and/or lighter present the tendency of floating, resulting in segregation and poor mixture quality. This segregation tendency resulting from particles properties makes difficult the determination of U_{mf} for the binary mixtures (Chiba *et al*., 1979).

These mixtures composed by different particles tend to separate in the vertical direction of the bed under fluidization conditions. The non-uniform distribution of solid components is caused by the competition between the mixing and segregation mechanisms (Qiaoqun *et al*., 2005; Huilin, *et al*., 2003). Examples of processes where the presence of different types of materials are used include coal and biomass gasifiers/combustors and more recently chemical recirculation systems (Alghamdi *et al*., 2012). The segregation would bring, in some cases, a strong lack of homogeneity, partial defluidization resulting in a reduction of the process performance (Formisani *et al.,* 2010).

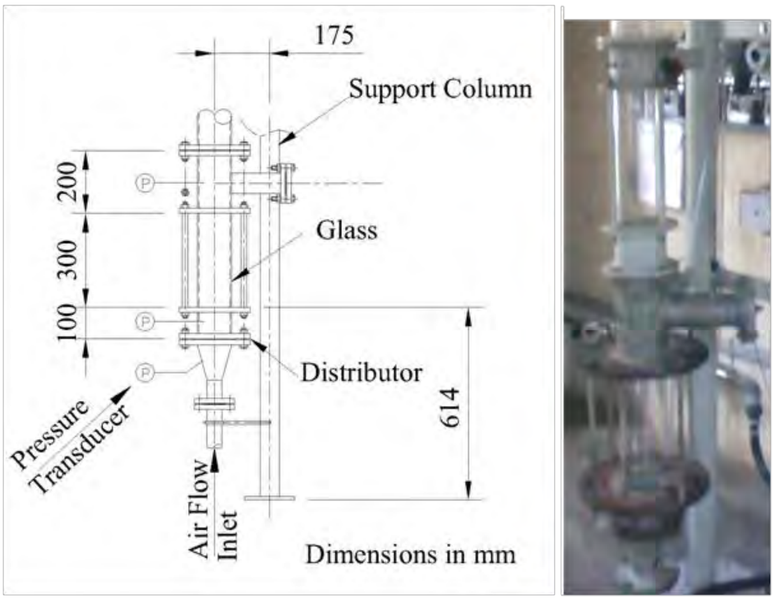
Wu and Baeyens (1998) showed that beds containing binary mixtures behave differently from reality if the mean density value of the two particles is taken into account. This paper presents an experimental study of multi-tuyere gas distributors using a sugarcane bagasse-sand mixture as bed material, in order to verify the influence of the nozzle geometry on the minimum fluidizing velocity range of the binary mixture and fluidization quality.

2. EXPERIMENTAL SYSTEM, MATERIALS AND METHODS

2.1 Experimental system

The experimental system used in this work is located in the Laboratory of Thermal Processes and Environmental Engineering at University of Campinas (School of Mechanical Engineering). This system is mainly composed by: (i) main column which is divided into three regions: plenum, gas distributor and riser, where pressure transducers are attached; (ii) centrifugal fan for supplying the air to the system; and (iii) orifice flow meter for providing the measurement of the air flow rate into the system. A schematic diagram of the fluidized bed main column is shown in Fig. 1.

The main column was built with sections of borosilicate glass, which allows the flow visualization, and carbon steel. The internal diameter of the main column is 0.10 m and the height is 2.5 m. The riser presents a thickness of 5 mm. The airflow control was made by a globe valve and the fine adjustment was made by a ball valve type.



(a) (b)

Figure 1. (a) Schematic diagram of the fluidized bed column (b) Picture of the main column.

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The air flow rate was measured using an orifice plate built according to ASME STANDARD MFC-14M (2003). The pressure drop measurements of the orifice plate and pressure drop across bed was performed using SMAR pressure transducers, model LD301. The gas temperature was measured by a type T thermocouple.

An exploded view of one tower of the gas distributor, tuyere type, is shown in Fig. 2. The gas distributor consists of a metal plate with seven holes M10x1.5 to connect the seven towers or tuyeres to be studied. The intention was to make a versatile gas distributor in order to study different tuyeres geometries as required by the experimental design applied in this research.

For this reason, it was built a tower that was removable and with changeable gloves in order to produce different geometries by changing the glove position around the tuyere.

Figure 2 shows an exploded view of the tuyere designed for this study which presents a central column, perforated glove and top layer. The central column was made of carbon steel and presents a central hole, that allows the entrance of the air flow and two holes in the rear position for the air flow exit, perpendicular to the axial direction.

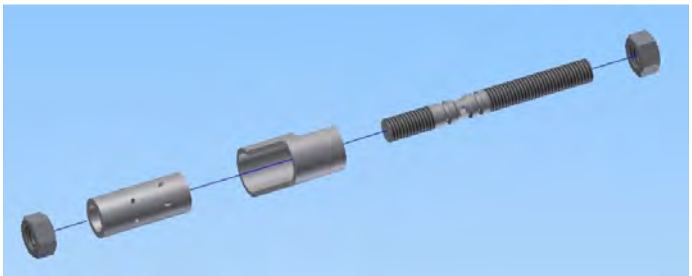


Figure 2. Exploded view of one tower of the tuyere distributor designed

The gloves were manufactured in aluminum, with two rows of drilling, one straight (presenting six orifices) and one with a 45° angle (presenting six orifices). In each experiment only one side of the glove must be functional. Because of that, the central column has two slots for the insertion of seal rubber rings to isolating one row of the drilling gloves.

Thus, only part of the glove holes distributes the air to the bed. The central column has two threaded at both ends of the tower for fastening insertion to the distributor plate and two nuts that hold the gloves at the desired height.

Finally, the top layer was made of aluminum, with a rubber blanket sandwiched inside, to adhere to the surface of the glove avoiding the gas flow to some orifices when desired. This procedure reduced the number of orifices from six to four or two.

2.2 Solid Materials

The solid materials used in this research were sugarcane bagasse and sand material. Its properties (size and density) are shown in Tab.1. Both materials belong to Geldart's group B. To determine the Sauter diameter for sugarcane bagasse sieves between 14 mesh (aperture diameter equal to 1.19 mm) and 325 mesh (aperture diameter equal to 0.045 mm) were used. The sand particles diameter range is from 0.07 to 1.12 mm.

Table 1. Sugarcane bagasse and sand properties: mean Sauter diameter (dp) and particles density (ρ_p)

Material	dp (10^{-6} m)	ρ_p (kg/m^3)
Sugarcane bagasse	386	961
Sand	293	2670

A binary mixture composed by 5 wt% of biomass and 95 wt% of sand was prepared and well-mixed before introducing inside the riser. The mixture density (ρ_{mix}), obtained by picnometry, for a well mixed material was 2460 kg/m^3. This value was used to verify the fluidization quality by comparing the bed density at different positions, after the fluidizing process, with different configurations of the gas distributor.

2.3 Methodology

Four variables were chosen as important design factors to the experimental design:

(i) Number of orifices (n_{or});

(ii) Orifices diameter (d_{or});

(iii) Angle of the gas jet in the vertical direction (α);

(iv) Alignment angle (β).

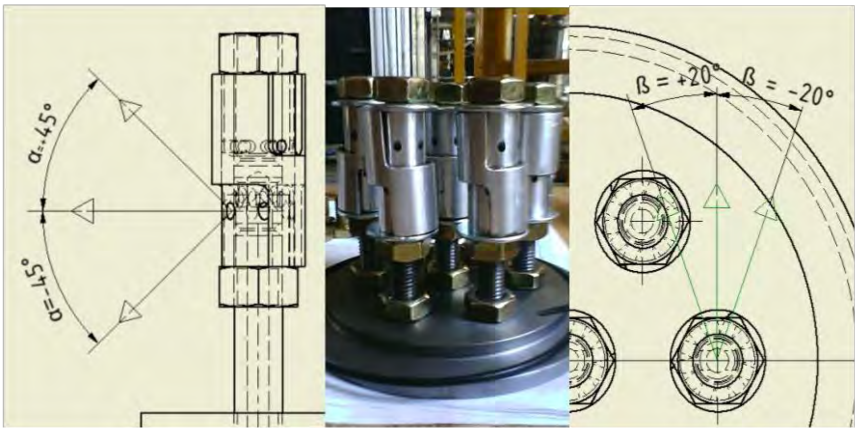
Based on the previous sections, the geometrical characteristics of the gas distributor were changed to verify its influence on the fluidization quality. Table 2 describes the chosen variables and studied ranges of operation.

Table 2. Studied geometrical factors of the gas distributor (tuyere type)

Studied geometric parameter	Statistical levels		
	–1	0	1
n_{or} (Number of orifices)	2	4	6
d_{or} (Orifices diameter)	1.5 mm	2.0 mm	2.5 mm
α (The angle of the gas jet)	-45º	0º	+45º
β (Alignment angle)	- 20º	0º	+ 20º

The number of orifices (n_{or}) is related to the number of orifices to be arranged in the tuyere for the airflow. The aim was to increase the flow velocity by reducing the open area and directing the flow, which is governed by the angle of alignment.

Figure 3 (b) shows the distributor used in the experiments. The value of the alignment angle was measured relative to the tangent of the primitive diameter of the holes of distributor plate (ranging from -20 º to +20 º). The alignment angle (β) can be seen in Fig. 3 (c).



(a) (b) (c)

Figure 3. (a) Schematic of alignment angular positioning of the towers; (b) Picture of distributor design used in this paper and (c) Schematic of alignment angle of the gas jet in the vertical direction of the tower.

The other parameter analyzed was the angle of the gas jet in the vertical direction (α), which shows the influence of the drill when the gas flow is directed at an angle of 45 ° up or down in relation to the perpendicular plane to the bed axis, in addition to the central position equal to 0 °. The angle of the gas jet in vertical direction could be seen in Fig. 3(a). Finally, the orifice diameters (d_{or}) tested was 1.5, 2.0 and 2.5 mm.

2.3.1 Minimum fluidizing velocity

Seeking preliminary answers about the binary mixture fluidization process a fractional factorial design was chosen. The four factors and the two levels indicated in 8 permutations runs and three central or standard points were used to evaluate the experimental error. The minimum fluidizing velocity was determined using the conventional method by measuring the pressure drop across the bed as a function of the superficial gas velocity. For this, the bed was suspended until a well-mixed bed was observed and then the gas flow was reduced gradually by closing the globe valve.

The valve was close every 20 seconds. For each valve opening, measurements of pressure upstream of the orifice plate, pressure drop across the orifice plate and the inlet air temperature were made to obtain the air mass flow rate. Additionally, the pressure drop between the plenum and the expansion chamber (freeboard) was measured in order to obtain the bed pressure drop to the construction of the hydrodynamics curve.

The hydrodynamics curve in Fig. 4 help us to determinate tree values of minimum fluidizing velocities: $U_{mf,i}$, U_{mf} and $U_{mf,c}$. The value of the initial fluidizing velocity ($U_{mf,i}$) is related to the point where the curve moves away from the fixed bed straight region. The velocity U_{mf} represents the point where the intersection of the projection lines for the fixed bed region and for the complete fluidizing region occurs. The complete fluidizing velocity ($U_{mf,c}$) represents the value in which all the particles inside the bed are fluidized.

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Thus, the first value is related to the minimum fluidizing velocity of the biomass particles that are less dense than the sand particles. A good fluidization quality is associated with small differences between $U_{mf,i}$ and $U_{mf,c}$. Thus it is believed that the difference between these values can be an indicator of mixing and segregation.

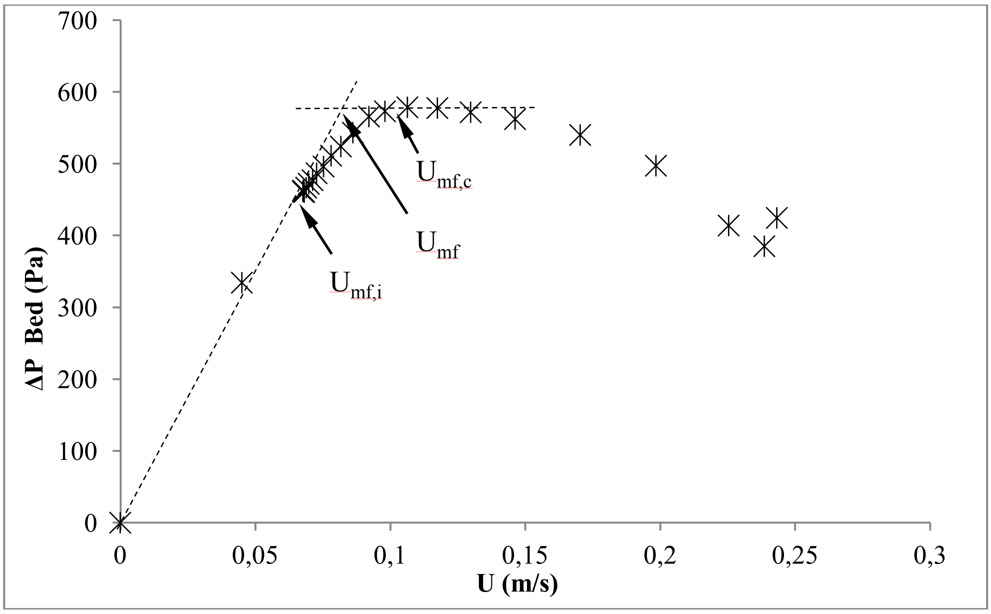


Figure 4. Methodology used to determine the minimum fluidizing velocities ($U_{mf,i}$, U_{mf} and $U_{mf,c}$).

Figure 5 shows the different gas-solid regimes behaviors that occurred during the tests. For each run, the bed started at a turbulent flow behavior and, with successive reduction in the airflow, bubbling regime is reached. The air flow rate is reduced until the fixed bed regime is reached.

(a) (b) (c)

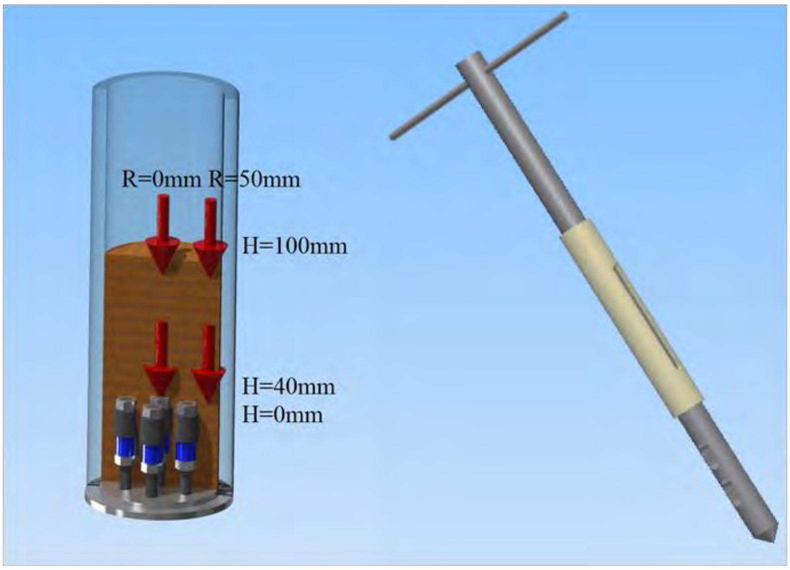
Figure 5. Different behaviors found in the tests: (a) Fixed Bed; (b) Bubble bed and (c) occurrence of preferential channels

2.3.2 Bed density at different positions inside the bed

Another analysis to study the mixture in the bed, was the sampling the material in different heights and radial positions to measure the behavior of the bed mixture density (ρ_{mix}) and compare to the ideal density for a homogeneous mixture of 5 wt%.

Figure 6 (a) shows the four regions where samples of bed material were collected. It is known from the literature that segregation occurs in layers along the height and in the radial direction for beds containing mixture of particles.

Therefore, H = 0 mm corresponds to the top face of the distributor towers. The first sampling height was 40 mm above the distributor, in both radial regions, at the central position of the bed as R = 0 mm and the position next to the wall R = 50 mm. Also, samples collection was repeated for H = 100 mm near the freeboard region. To collect the material in the bed in different positions, we started with a homogeneous mixture of biomass and sand, which took up the bed to the maximum airflow and stands in this condition for 5 minutes. After this period, it was quickly cut the airflow, so then as to collect material the collection was made with the sampling probe showed in Fig. 6 (b).



(a) (b)

Figure 6. (a) Schematic of samples regions of the bed (b) Design sampling probe.

The sampling probe was composed by tree parts made in aluminum:

- Solid shaft, with two sampling cavities to collect material in the bed.
- Sleeve, to prevent collect sampling material from the bed while the shaft is not located in the correct layer of material region and to confine the sampled material in the cavity and removal from the bed
- Round bar, for help handling the probe in bed.

2.4 Experimental design and analysis method

In this stage, we have two points to be evaluated: one taking into account the measurements of material density from the bed (in different radial and axial positions) and its deviation from the density of the mixture fed into the bed, which was fix in 5 wt% of bagasse. The other point was to check the difference of the values of minimum fluidizing velocities obtained from the hydrodynamics curve.

3. RESULTS AND DISCUSSION

3.1 Minimum fluidizing velocity

Table 3 summarizes the results for the minimum fluidizing velocity data obtained for the 11 performed tests using experimental design and the Statistical analysis. Literature review show that the difference between $U_{mf,i}$ *and* $U_{mf,c,}$ decreases as the the bed homogeneity increases. The values of effects obtained from experimental design analysis were: -0.184 (n_{or}), 0.181(d_{or}), 0.169(α), -0.149(β) and the standard error were 0.133.

Thereby, analyzing the values it is possible to verify that for variables number of holes (n_{or}) and alignment angle (β) the effects were negative. However, for the diameter of holes (d_{or}) and angle of the gas jet in the vertical direction (α) the effects were positive. It is also possible to observe that they showed the same order of the error introduced by the measuring of the central point. Because of that, it is not possible to say that results are statistically relevant to the analysis.

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Table 3. Experimental data for Minimum fluidizing velocity

Runs	n_{or}	d_{or}	α	β	Minimum fluidizing velocity (m/s)		
					$U_{mf,i}$	U_{mf}	$U_{mf,c}$
1	- (2)	- (1.5)	- (-45º)	- (-20º)	0.092	0.065	0.156
2	+ (6)	- (1.5)	- (-45º)	+ (20º)	0.07	0.090	0.157
3	- (2)	+ (2.5)	- (-45º)	+ (20º)	0.04	0.083	0.131
4	+ (6)	+ (2.5)	- (-45º)	- (-20º)	0.06	0.080	0.114
5	- (2)	- (1.5)	+ (45º)	+ (20º)	0.05	0.088	0.127
6	+ (6)	- (1.5)	+ (45º)	- (-20º)	0.08	0.087	0.124
7	- (2)	+ (2.5)	+ (45º)	- (-20º)	0.05	0.078	0.127
8	+ (6)	+ (2.5)	+ (45º)	+ (20º)	0.06	0.087	0.132
9	0 (4)	0 (2.0)	0 (0º)	0 (0º)	0.05	0.080	0.114
10	0 (4)	0 (2.0)	0 (0º)	0 (0º)	0.05	0.086	0.119
11	0 (4)	0 (2.0)	0 (0º)	0 (0º)	0.05	0.083	0.118

Figure 7 presented the Pareto diagram for these analyses where there are present the most important effects for the values of minimum fluidizing velocity. They are arranged on the chart in descending order of importance (n_{or}, d_{or}, α, β). However, as discussed before, it is not possible to obtain a statically significant result for these effects at a significance level of 5% P-value (Limit indicated for the red dashed line).

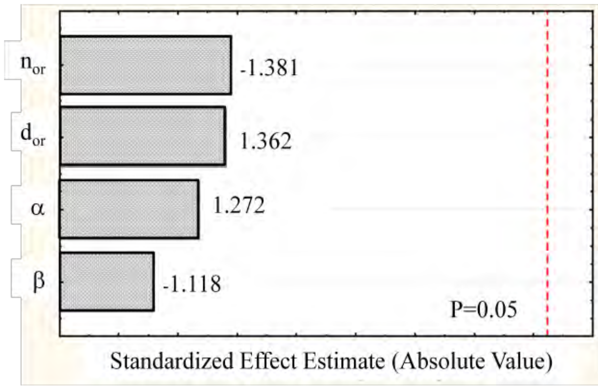

Figure 7. Pareto Diagram for the effect of Minimum fluidizing velocity.

The statistical significance of the variables was evaluated by observing whether the horizontal bars, representing the factors interactions, are beyond the vertical reference line on the level of significance of the P-value.

3.2 Bed density at different positions inside the bed

Table 4 shows the results of bed density mixture measured from samples collected in two different heights and two different radial positions. The table is divided into two parts. The left part refer the sampling values of mixture density (ρ_{mix}) obtained by picnometry and the right one refers the variation of these values to the ideal 5% wt biomass. The definition of ρ_{mix} is showed in the Eq. (1).

$$\rho_{mix} = \frac{(inert\ mass)+(bagasse\ mass)}{(volume\ of\ mixture)} \quad (1)$$

These values were used to check the quality of fluidization, ie, the focus in order to reduce the differential density values to optimize the mixing and reducing the effect of segregation.

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Table 4. Experimental data for mixture mass density

Runs	ρ_{mix} (kg/m³)				$\Delta\rho_{mix} = \lvert\rho mix - 2460\rvert$ (kg/m³)			
	H=100 mm		*H=40 mm*		*H=100 mm*		*H=40 mm*	
	R=0mm	*R=50mm*	*R=0mm*	*R=50mm*	*R=0mm*	*R=50mm*	*R=0mm*	*R=50mm*
1	1855	1945	1266	1548	605	515	1194	912
2	1444	1505	1003	1331	1016	955	1457	1129
3	2082	2183	1841	1594	378	277	619	866
4	1418	1936	1353	1471	1042	524	1107	989
5	1195	2208	1128	1398	1265	252	1332	1062
6	1341	1605	1200	1345	1119	855	1260	1115
7	2283	2243	1021	1267	177	217	1439	1193
8	1860	2159	1159	1269	600	301	1301	1191
9	1689	1749	1459	1514	771	711	1001	946
10	1442	1838	1077	1286	1018	622	1383	1174
11	504	1942	863	1258	1956	518	1597	1202

The analysis of effect for the experimental design data of mean bed mixture density variation were: 0.228 (n_{or}), -0.239(d_{or}), 0.068(α), -0.016(β) and the standard error was 0.077. It is possible to see that the error showed the lower order of effect values of two variables n_{or} and d_{or}. In the case of the number of holes (n_{or}) and the angle of the gas jet in the vertical direction (α) the effect is positive. This means that, for the studied factor that has a positive effect when its value is increased the density variation also increases, contrary to the expected behavior. However, for the orifice diameter (d_{or}) and the alignment angle (β) the effects were negative. By analogy, if their values were increased it will be more close to the expected results.

For significance analysis of these results was performed by calculation of p-value and comparison with the significance of the effects of variables by Pareto diagram Fig. 8.

The Pareto Diagram shows the magnitude of the t-Student (t) at 90% confidence level. The factor n_{or} is statistically significant and has an effect of increasing segregation with increasing its value, or number of orifices. Therefore the range of this parameter should be reduced in future work. As for the factor orifices diameter (d_{or}) was identified an adverse effect, in other words, increasing de diameter the difference between the desired density decreases, resulting in a improvement on fluidization quality.

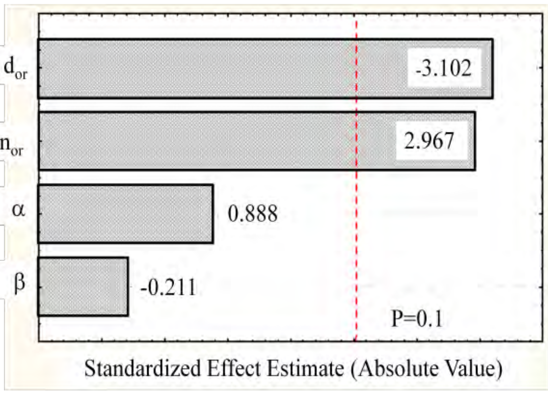
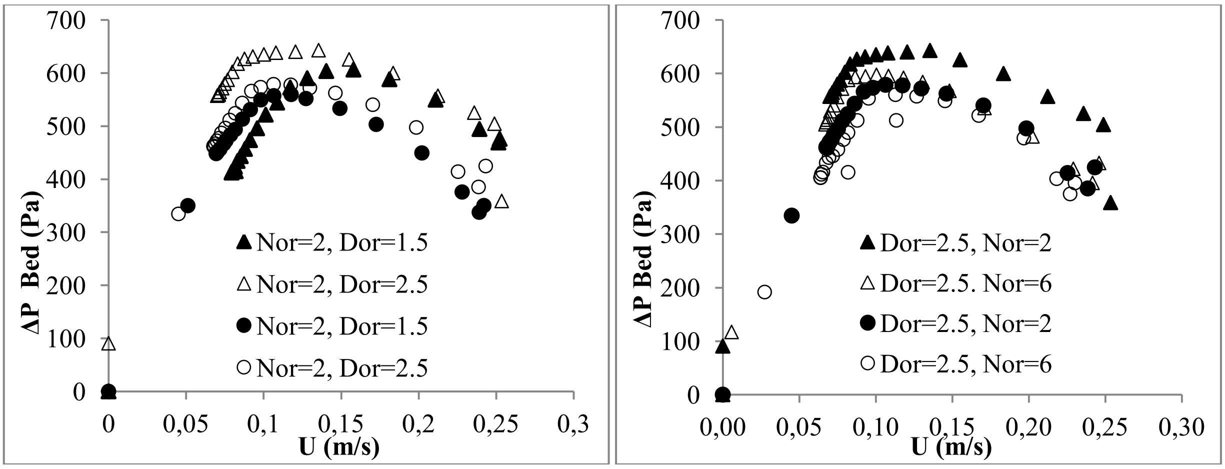


Figure 8. Pareto Diagram for the effect of for mixture mass density.

One-way to visualize this influence, the parameters n_{or} and d_{or}, is by analyzing the superficial gas velocity versus pressure drop in the bed. Thus, it can be seen in Fig. 9 (a) that increasing the diameter of the orifices and keep the number of orifice promotes an increase on the bed pressure drop and bring the curve closer the tangent drawing line of fixed bed and the horizontal line of complete fluidization, ie, the difference between the initial fluidization and complete fluidization decreases and a higher homogeneity in the bed is observed. This tendency can also be seen when we keep the orifice diameter of the tuyere and reduce the number of orifices, Fig. 9 (b).



(a) (b)

Figure 9. Hydrodynamics curves modifications for the two statistical relevant variables: (a) d_{or} (b) n_{or}.

The observed reduction on the bed pressure drop in the fluidized bed region is attributed to preferential channels as shown in Fig. 5(c).

4. CONCLUSION

The proposed tuyere type distributor showed to be versatile and appropriate to study the influence of four geometric factors (number of holes, holes diameter, angle of drilling and alignment angle) on the mixing quality between the inert material (sand) and biomass (sugar bagasse).

The hydrodynamics curve allowed to verify the influence of the studied geometrical parameters on the fluidization process. Density values of samples collected inside the bed have identified two factors statistically relevant to the mixing process inside the bed: the number and diameter of the tuyere orifices.

The optimization of geometrical parameters selected for the process of mixing and segregation of biomass in the bed containing inert material will only be proven by performing new experimental designs that will be made in the continuity of this research.

The results allow us to propose other ranges of values regarding the two identified geometric factors as important to the mixing phenomena, in order to maximize the effects of these parameters. It is expected that this work can contribute to the technological development of gas distributors type tuyere applied to binary systems involving biomass and sand.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Alghamdi, Y.A., Peng, Z.B., Doroodchi, E., Moghtaderi, B., 2012. "Cfd-DEM simulation of mixing and segregation of fluidized binary mixtures of particles with different sizes and densities". In *Proceedings of the 21st Int. Conf. on Fluidized Bed Combustion*, pp. 1-7.

ASME MFC-14M, 2003. "Measurement of Fluid Flow using Small Bore Precision Orifice Meters – An American National Standard", The American Society of Mechanical Engineers, USA.

Basu, P., 2006. *Combustion and gasification in fluidized beds*. Taylor & Francis.

Chiba, S., Chiba, T., Nienow, A.W., Kobayahi, H., 1979. "The minimum fluidizing velocity, bed expansion and pressure-drop profile of binary particle mixture". *Powder technology*, Vol. 22, pp. 255-269.

Dong, S., Cao, C., Si, C., Guo, Q., 2009. "Effect of perforated ratios of distributor on the fluidization characteristics in a gas-solid fluidized bed". *Ind. Eng. Chem. Res.*, Vol. 48, pp. 517-527.

Formisani, B., Girimonte, R., Vivacqua, V., 2011. "The relationship between fluidization velocity and segregation in two-component fluidized beds: A preliminary analiysis". In *Proceedings of the 10th International Conference on Circulating fluidized Beds and Fluidization Technology - CFB-10,* pp. 672-679. Sunriver, Oregon, USA.

Geris, M.V.A., Arnao, J.H.S., Pécora, A.A.B., 2011. "Experimental study of gas distributors for fluidized beds containing sand-bagasse mixtures". In *21st International Congress of Mechanical Engineering, COBEM2011,* Natal, Brazil.

Guo, Q., Werther, J., Aue-klett, C., Hartge, E., 2005. "Flow misdistribution at bubble cap distributor in a plant-scale circulating fluidized bed riser". *AIChE Journal*, Vol. 51, pp. 1359-1366.

Hilal, N., Ghannam, M.T., AnabtawiI, M.Z., 2001. "Effect of bed diameter, distributor and inserts on minimum fluidization velocity". *Chemical engineering technology*, Vol. 24, pp.161-165.

Huilin, L., Yurong, H., Gidaspow, D., Lidan, Y., Yukun, Q., 2003. "Size segregation of binary mixture of solids in bubbling fluidized beds". *Powder technology*, Vol. 134, pp.86-97.

PDE-2021, 2013. "Plano Decenal de Expansão de Energia 2021. MINISTÉRIO DAS MINAS E ENERGIA." Jan. de 2013. <http://www.epe.gov.br/PDEE/Forms/EPEEstudo.aspx>.

Qiaoqun, S., Huilin. L., Wentie, L., Yurong, H., Lidan, Y., Gidaspow, D., 2005. "Simulation and experiment of segregating/mixing of rice husk-sand mixture in a bubbling fluidized bed". *Fuel,* Vol. 84, pp. 1739-1748.

Wormsbecker, M., Puglseyt, T.S., Tanfara, H., 2007. "The influence of distributor design on fluidized bed dryer hydrodynamics". *Proceedings of the 12th International Conference on Fluidization – New horizons in fluidization engineering,* pp. 815-822. Vancouver, Canada.

Wu, S.Y. and Baeyens, J., 1998. "Segregation by size difference in gas fluidized beds". *Powder technology*, n. 98, pp. 139-150.

Zhu, J., Xu, J., Peng, B., Zhang, C., 2011. "The effects of distributor design on the solids distribution in a CFB riser". In *Proceedings of the 13th Int. Conference on Fluidization.* Gyeong-ju, Korea.

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