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PRESSURE DROP IN A COLD BENCH-SCALE CIRCULATING FLUIDIZED BED SYSTEM FED WITH TERNARY MIXTURES

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Abstract. *This work analyzes the static pressure drop behavior in main components of a bench-scale circulating fluidized bed (CFB) when ternary mixtures of solids are fluidized at cold conditions. The CFB loop, which is composed by a 0.078 m internal diameter and 2.7 m height riser, a tangential cyclone, a 0.053 m internal diameter standpipe and a L-type valve for solids recirculation was fed with mixtures of fuel particles (saw dust and coal) and quartz sand. The experimental program followed a 2^2 factorial design with duplicated runs, in which the total solids inventory varied from 3.5 to 5.0 kg, and the mixture fraction (mass of fuel particles/mass of fuel particles and sand) from 0.025 to 0.05. In tests, the fluidizing gas velocity was 4.0 m/s and the proportion of coal to biomass was 1:1. From results for total solids inventory of 5.0 kg was verified that the higher the mixture fraction (more bed volume) the higher the pressure drop in all components because of the wall friction increases. This effect was less critical for total solids inventory of 3.5 kg, but also significant at 95% of confidence level. A semi empirical mathematical model was proposed for simulating the pressure drops across the system and comparing them with experimental data.*

Keywords: *Circulating fluidized bed, ternary mixtures, coal, saw dust, pressure drop.*

1. INTRODUCTION

Circulating Fluidized Bed (CFB) is a technology with applications in areas of energy conversion and petro-chemical processes, mineral and physical processing, as well as, in chemical and pharmaceutical. A major attention is given for combustion, and more recently, for the co-firing process involving ternary mixtures of fossil fuel, biomass and inert material. The co-firing in circulating fluidized beds has showed advantages associated to high burning efficiency and low emissions, which are strongly dependent on hydrodynamics of the solid mixture (Sun, *et al.*, 2013; Gungor, 2013).

The pressure drop of the gas-solid flow in each component of the CFB system is a hydrodynamic parameter driven by the pressure balance around de loop, which is composed by a riser, cyclone, standpipe and a valve controlling the particle circulation by using mechanical or non-mechanical parts (Basu, 2006). The pressure balance around a CFB loop has been studied by several researches. Kim *et al.* (2002) analyzed the static pressure drop profile in a pilot scale CFB operating with only sand particles. They found that the total solids inventory and the fluidizing gas velocity affect the mass solid distribution and, consequently, the pressure drop in components of the system.

In the case of binary mixture of solids, previous works (Rao and Bheemarasetti, 2001; Formisani and Girimonte, 2003; Sahoo and Roy, 2008; Paudel and Feng, 2013) have mainly focused on determining other hydrodynamic parameters, such as the minimum fluidizing gas velocity, or identifying gas-solid phenomenon such as segregation, which are variables of special interest when operating bubbling fluidized bed units. On the other hand, studies on hydrodynamics of ternary or multi-component mixture of solids in bubbling and circulating fluidized beds are scarce in literature. Jena, *et al.*, (2008) and Asif (2013) carried out studies focused to the gas-solid pressure drop and the minimum fluidizing gas velocity of beds containing more than two kinds of solids.

This paper intends to contribute with an experimental analysis of the static pressure drop around the loop of a bench-scale circulating fluidized bed operated to cold conditions and composed by ternary mixtures of Brazilian coal, sawdust and quartz sand, taking into account the mixture ratio of fuel particles in bed and the total solids inventory.

2. MATERIALS AND METHODS

2.1. Experimental setup

Figure 1 illustrates the experimental apparatus used in this study, which consist of a bench-scale circulating fluidized bed unit specially designed for hydrodynamic tests at atmospheric conditions (Valaszek and Marin, 2013). It was assembled in modules made of carbon steel (sections *BL-1*, *BL-3*,*BL-5*, *BL-7*, *BL-8, BL-10,* cyclone and *VL*) and acrylic material (sections *BL-2*, *BL-4*, *BL-6*, *BL-9*, *BL-11*) for allowing the gas-solid visualization through the CFB loop.

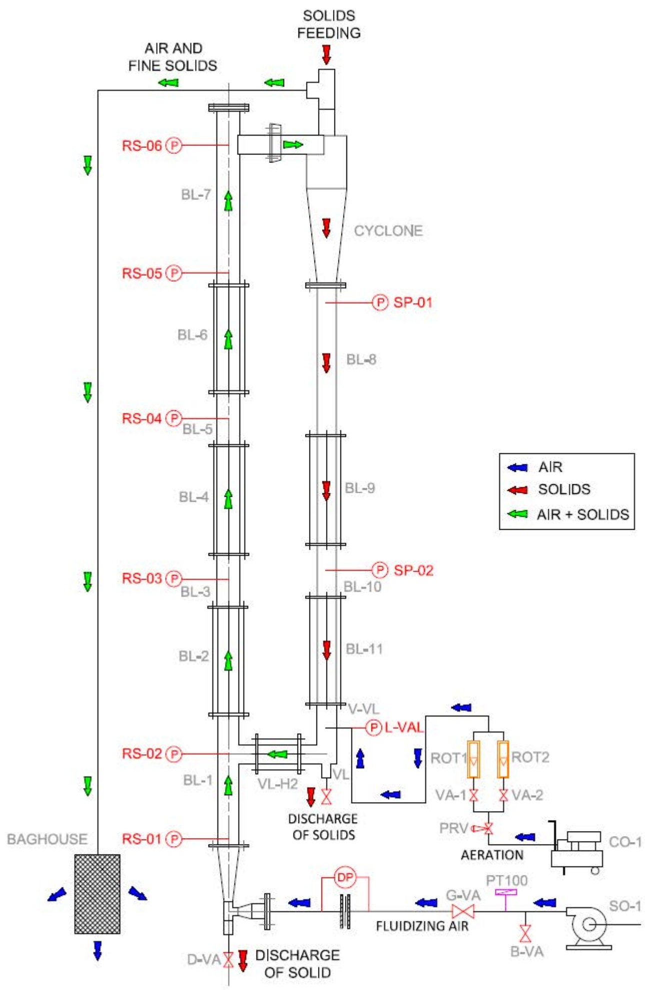

Figure 1 - Experimental apparatus

The fluidization loop is composed by a riser with internal diameter of 0.078 m and height of 2.7 m, a tangential cyclone with main diameter of 0.145 m, a standpipe with internal diameter of 0.053 m, and an L-valve for recycling solids. Several pressure taps connected to U-type manometers were placed around the loop to measure the static pressure of the gas-solid flow. In riser, the differential pressure was obtained by measurements in taps *RS-02* and *RS-06*, similarly in cyclone by taps *RS-06* and *SP-01*, and in the standpipe by taps *SP-01* and *L-VAL*. In the L-valve, the respective differential pressure was measured in the section including the horizontal length and the aeration point (taps *L-VAL* and *RS-02*). The measurements of static pressure registered by tap *RS-01* were ignored because it is not included in the path of the circulating solids.

Two pressure taps localized upstream and downstream of an orifice plate meter with hole diameter of 25 mm were used to determine the fluidizing air flow rate, and consequently the fluidizing gas velocity attained in the riser base. The fluidizing air was provided for a 4 hp radial blower (*SO-1*), and controlled by using a gate valve (*G-VA*). In some cases, the auxiliary bypass valve (*B-VA*) is used in order to avoid excessive pressurization of the duct. Also, a thermal resistor *PT-100* was included in the air line for correcting the fluidizing gas velocity into the riser. On the other hand, the aeration air injected into L-valve for recycling solids is supplied for a 2.0 hp reciprocating compressor (*CO-1*). This air line has a pressure regulating valve (*PRV*) and needle type valves (*VA-1* and *VA-2*) for controlling the air flow measured by two rotameters (*ROT1* and *ROT2*) connected in parallel array. A fabric filter (baghouse) was added at the end of the exhaust line to capture fine particles.

2.2. Characterization of bed particles

Experimental tests were carried out using mixtures composed of three solid materials: quartz sand (inert particle), mineral coal of Paraná State and pine sawdust (fuels). The solids were characterized in terms of following properties: particle mean diameter, particle density, particle sphericity and particle transport velocity, as shown in Table 1.

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Table 1 – Properties of solids used in experimental tests

Solids	**Mean diameter (μm)**	**Density ($kg.m^{-3}$)**	**Sphericity**	**Transport velocity ($m.s^{-1}$)**
Quartz sand	256	2,522	0.69	3.09
Mineral coal (Paraná State)	513	1,433	0.60	3.22
Pine sawdust	725	520	0.45	2.30

The mean diameter for each bed material was obtained through separation process carried out in standard and sequential opening size sieves. The apparent density of the particles of quartz sand and mineral coal were measured by pycnometry in water and ethanol, respectively, whereas for the pine sawdust the density was adopted from literature (Zen *et al.*, 2007), due to lack of appropriate device for carry out the measure. The sphericity of the particles was found using the method proposed by Massarani and Peçanha (1989) *apud* Cortez *et al.* (2008), wherein the value of sphericity of the particle is calculated from the ratio between the inscribed and circumscribed diameters of the solids particles. Finally, the transport velocity of particles in the riser (u_{tr}) [m/s] is determined by the equation proposed by Perales (1991), valid for flows where the Archimedes number is between 20 and 50,000.

2.3. Experimental planningand test procedure

The conditions tested in the CFB loop were defined taking into account an experimental planning based on factorial design. In this study, a 2^2 factorial experimental design was chosen, in which two controllable factors are analyzed in two levels (high and low), causing effects on one or more response variables (Barros, *et al.*, 2003). The input variables were the total solids inventory and the mixture ratio (mass ratio of fuels and total bed particles).Preliminary tests suggested a minimum solids inventory close to 3.5 kg to avoid hydrodynamic instability or shortcut of the gas-solid flow due to lack of particles into the system, and a maximum close to 5.0 kg to avoid the slug flow (slugging) in the standpipe or the solids interference in the lower section of the cyclone due the excessive bed column height formed in the standpipe. On the other hand, the appropriated mixture ratio was chosen based on literature data, which suggest the presence of fuel in the CFB at maximum proportion of 5.0% for applications in thermochemical processes (Basu, 2006). Thus, final tests were defined considering a mixture ratio of 2.5% and 5.0%, all of them with fixed mass proportion of 1:1 between the two solid fuels. Table 2 shows the final experimental conditions tested, which were carried out in replicate in order to determine both the pure error of measurements and the statistical significance of results.

Table 2. Combinations of solids inventory and mixture ratio used in experimental tests.

Test	**Solids Inventory (I_T)**		**Mixture Ratio (M_R)**	
	Level	**Value (kg)**	**Level**	**Value (%)**
1	+	5.0	+	5.0
2	+	5.0	-	2.5
3	-	3.5	+	5.0
4	-	3.5	-	2.5

In each test, the mixture of bed particles was previously fed through the upper region of the cyclone, as illustrated in Fig. 1. Thus, solids are initially accumulated in fixed bed regime at the bottom of standpipe and part of the L-valve. The blower is turned on and the fluidizing air across the riser up to the gas temperature becomes constant. After that, the aeration in the L-valve is activated and the solids begin to circulate around the CFB loop. Once the air temperature stabilizes with bed of solids, the measurements of the static pressure are carried out. At the end, the discharge of solids from the CFB loop is done in two points, one located close to the L-valve (*VL*) and another in the bottom of the riser.

2.4. Mathematical model

The semi-empirical mathematical model proposed in this work is an adaptation of the hydrodynamic model presented by Rodrigues and Beltrane (2011), by which the main dimensions of the bench-scale circulating fluidized bed (CFB) of Fig. 1 were determined. Modifications in this algorithm were included for simulating operational conditions of the system with information about particle characteristics and fluid properties previously defined. So, keeping fixed the geometry was possible to know the effect of the total solids inventory (I_T) and the mixture ratio (M_R) on the hydrodynamics, in especial, on the pressure drop across main components of the CFB system.

Regarding the fluidizing gas velocity, it was used a value above of the transport velocity in order to guarantee the presence of the fast fluidization regime. As described before, the solids inventory was based on preliminary tests to evaluate the capacity of the CFB unit, while the mixture ratio was defined according previous researches. So, the inflection point of the voidage profile (H_i) in riser and the internal recycle ratio of solids on top of the riser (R_S) become output variables.

The pressure balance around the CFB loop is expressed by Eq. (1):

$$\Delta P_{sp} = \Delta P_{sr} + \Delta P_c + \Delta P_{vl} \tag{1}$$

where ΔP_{sp} is the pressure drop in the standpipe. Considering the cyclone region, the total pressure variation (ΔP_c) is established by Eq. (2), according Basu (2006):

$$\Delta P_c = \Delta P_e + \Delta P_f \tag{2}$$

where ΔP_e and ΔP_f are the pressure variation in the inner vortex and due to friction on the cyclone wall, respectively. These terms are determined through Eq. (3) and (4):

$$\Delta P_f = f_w \frac{A_{sit}}{0.9Q} \frac{\rho_g}{2} (u_a u_i)^{\frac{3}{2}} \tag{3}$$

$$\Delta P_e = \left[2 + 3 \left(\frac{u_i}{v_i} \right)^{\left(\frac{4}{3}\right)} + \left(\frac{u_i}{v_i} \right)^2 \right] \frac{\rho_g}{2} v_i^{\ 2} \tag{4}$$

where f_w is the friction coefficient of the gas-solid flow; A_{sit} is the total internal area of the cyclone; Q is the gas flow entering the cyclone; u_a is the tangential velocity at the outer radius of the cyclone and v_i is the mean gas velocity in the exit tube. Both equations are dependent of the gas density (ρ_g) and tangential velocity in the internal diameter of the gas exit duct (u_i). All these terms can be found in detail in Basu (2006).

Another pressure variation is ΔP_{vl}, that represents the pressure drop in the L-valve. It occurs mainly due to the accumulation of solids into the horizontal length that connects the riser section with the aeration point.

$$\Delta P_{vl} = 216 \ \frac{G_{svl}^{\ 0.17}}{M^{0.63} D_s^{\ 0.15}} L_{ad} \tag{5}$$

where G_{svl} is the solids recycle rate through standpipe; M, the internal diameter in standpipe and L-valve; L_{ad}, the distance between the solids recycle point and aeration, and D_s, the particle Sauter diameter. For the specific case of two consecutives sieves, the Sauter diameter is equal to the average diameter of particle. The Sauter diameter is calculated according Eq. (6).

$$D_s = \frac{1}{\sum_{i=1} {x_i}/{d_i}} \tag{6}$$

where x_i is mass fraction of particles trapped in the mesh in each sieve and d_i is average opening between upper and lower sieves.

The pressure drop above the solids recycle point in the riser (ΔP_{sr}) can be calculated through the Eq. (7):

$$\Delta P_{sr} = \Delta P_r - g\,(1 - \varepsilon_a)\rho_s H_{sr} \tag{7}$$

where ΔP_r is the pressure variation for the entire length of the riser; ε_a, the average porosity in the bottom of the riser; ρ_s, the density of the solid particles; H_{sr}, the height of the solids recycle point, and g, the gravitational acceleration. The term referring to mixture density was found by Eq. (8).

$$\rho_s = \sum_{i=1}^{3} \rho_i \, x_i \tag{8}$$

where ρ_i is the average density of each kind of solids.

For solving the equations system of the mathematical model was used the software Engineering Equation Solver - EES ®.

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3. RESULTS AND DISCUSSIONS

3.3. Experimental results

As shown in Tab. 2, eight experimental tests were carried out. All tests had the following same operating conditions: coal to sawdust mass ratio (1:1); fluidizing gas velocity in the riser base (4 $m.s^{-1}$); aeration rate in the L-valve measured by the flowmeter (*ROT2*) between 0.55 and 0.6 m^3h^{-1} (0.72 to 0.77 $kg.h^{-1}$), and fluidization air temperature in the range of 42.0 to 50.5 °C.

3.3.1. Effect of solids inventory and mixture ratio on static pressure

Figure 2 shows the behavior of the static pressure for the gas-solid flow crossing the fluidized loop in function of the two controlled variables.

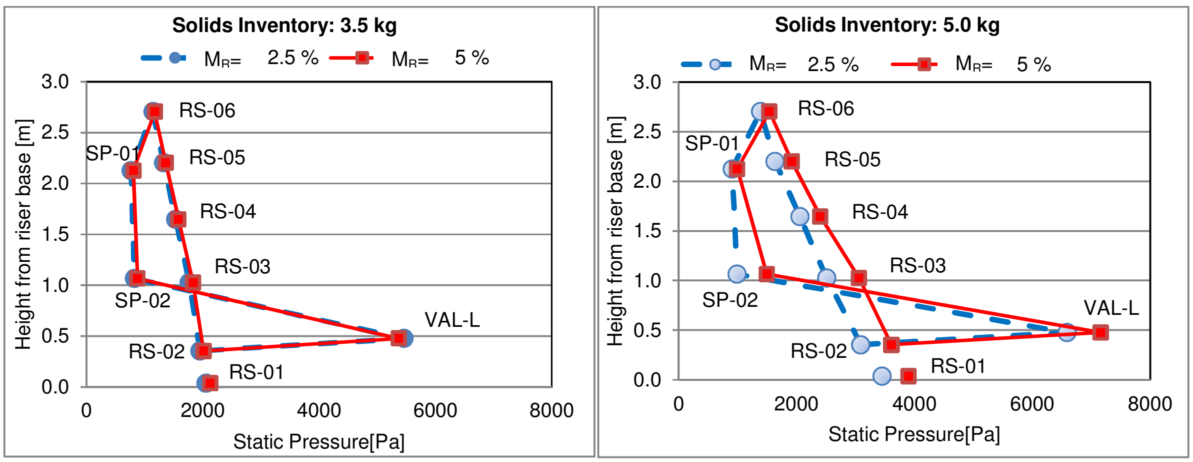

Figure 2 - Axial profile of static pressure in function of mixture ratio.
(a) solids inventory =2.5 kg; (b) solids inventory = 5.0 kg.

The results show that increasing the solids inventory in the bed tend to increase the static pressure in all components of the fluidization loop. This result was as expected because of the average voidage of the bed decreases with more mass being present around the system. On the other hand, it was observed that increasing both proportion of mineral coal and biomass in the bed also leads to higher static pressure levels in the system, but with more intensity at the high level of solids inventory (5.0 kg). The reason for this behavior is the combination of effects produced by diminution of the bed porosity (attributed in this case to the higher volume of particles present at same solids inventory) and the enhanced frictional forces on the walls due to more bed surface area. In addition, from Fig. 2 it can be observed that the highest pressure values were obtained in the standpipe section. This occurs due to the greater accumulation of particles above of aeration point in order to maintain the automatic control of the recycling solids flow driven by the pressure balance.

The standardized effect on the static pressure drop of solids inventory, mixture ration and combination of them is depicted in Fig. 3 and Fig. 4. Results obtained from Pareto charts suggest that the static pressure drop through the riser, cyclone and standpipe is mainly affected by the solids inventory at 95% of confidence level. More, in the riser, similar significant effects were obtained for the combination of mixture ratio-solids inventory and the mixture ratio only, whereas in standpipe, the combination of mixture ratio-solid inventory was more important than the isolated effect of solids inventory. In the region of the standpipe (Figure 4(a)), the static pressure increased with solids inventory as expected, since more mass of particles is accumulated in the column.

Figure 4(b) shows that the static pressure drop in the L-valve was not affected at 95% of confidence level by any controlled factor. This is explained because in the L-valve section (horizontal length to aeration point), the changes on mean bed porosity and the particle-wall superficial contact area were not important for the tested experimental conditions.

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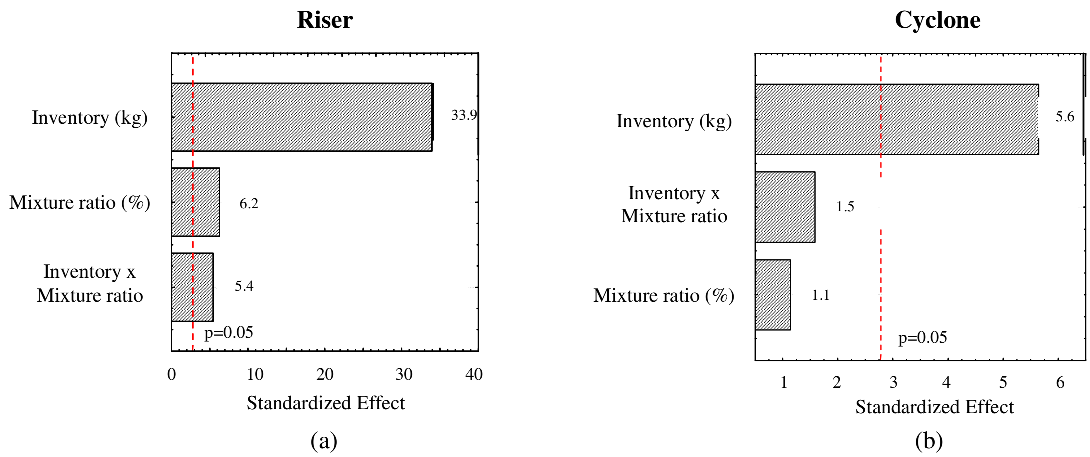

Figure 3 - Standardized effect of solids inventory and mixture ratio on the pressure drop in riser and cyclone components.

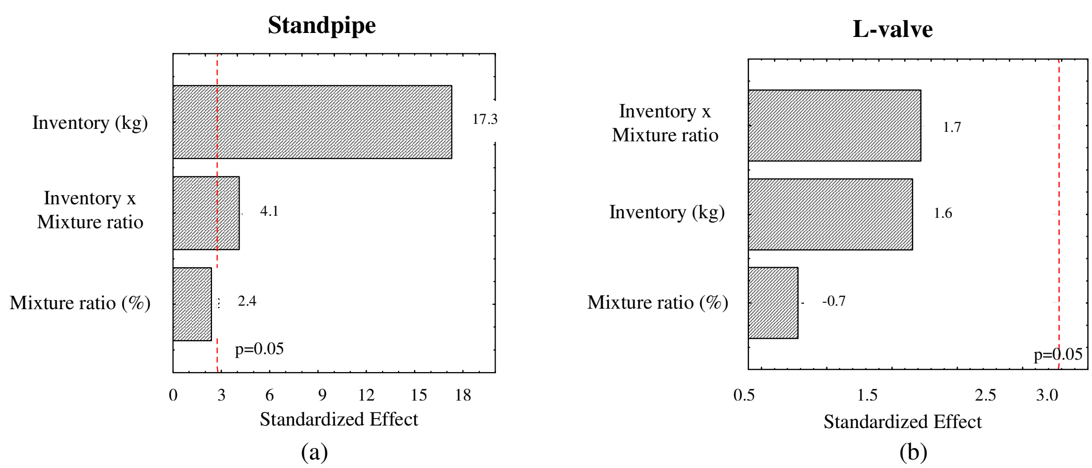

Figure 4 - Standardized effect of solids inventory and mixture ratio on the pressure drop in standpipe and L-valve components.

During experiments it was found that increasing the mixture ratio from 2.5% to 5.0%, the pressure drop in the L-valve decreases. This is because of the density of fuel particles is lower than the density of the inert particles. Thus, by injecting the same amount of air in the aeration point the fuels particles were transported easier toward the riser. This fact was confirmed by Arena et al. (1998), who found that the participation of more dense particles leads to increase the pressure drop in the L-valve section during its operation. However, once the pressure drop was not significant, more studies are needed because the effect of mean diameter and sphericity of bed particles were not taken into account.

3.4. Validation of the mathematical model

Figures 5 and 6 illustrate the results obtained from the mathematical model for the pressure drop in CFB components and those measured in experimental tests. Additionally, a column with deviation between both results is included at right side of each graph.

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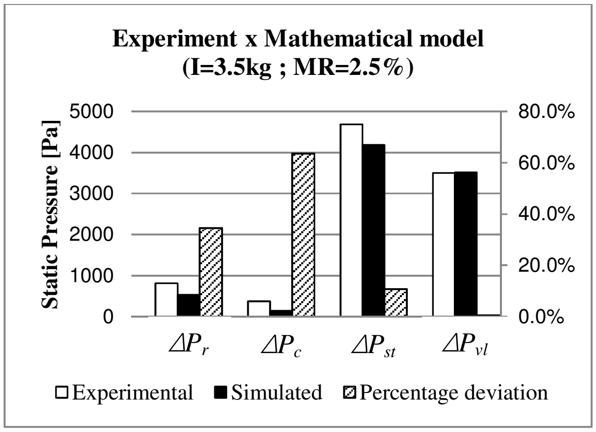
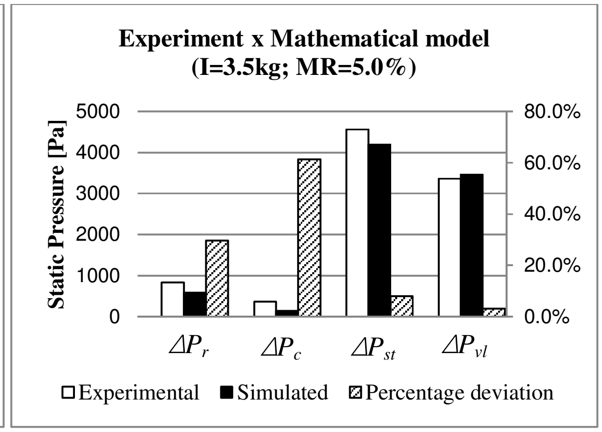
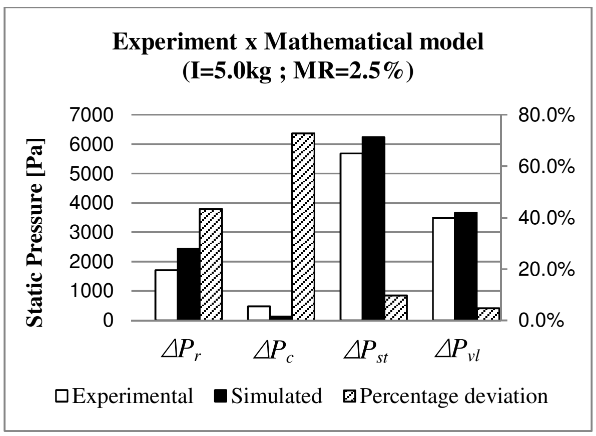


(a)

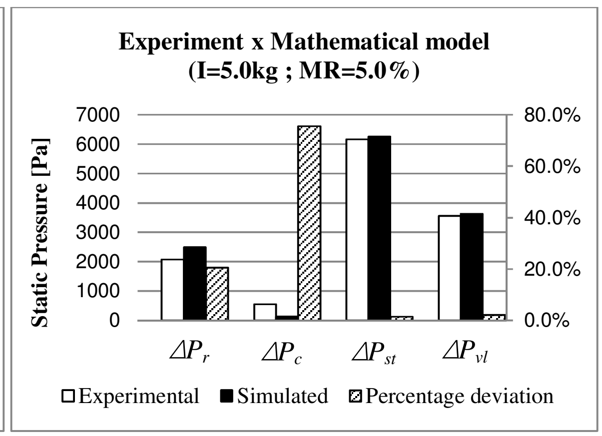


(b)

Figure 5 - Values of static pressure drop and deviation for experimental and simulated results in function of mixture ratio for low level of solids inventory.



(a)



(b)

Figure 6 - Values of static pressure drop and deviation for experimental and simulated results in function of mixture ratio for high level of solids inventory.

From Figs. 5 and 6 it can be seen that the highest values of static pressure drop simulated are those obtained in the standpipe (*ΔPst*) and L-valve (*ΔPvl*), which is in agreement with experimental results. This occurs because to the higher concentration of particles present in these sections, as compared to the riser and cyclone regions.

The highest values of deviation between experiment and mathematical model were found in the cyclone model (*ΔPc*). The static pressures measured and simulated in this component were very low. Thus, errors in reading manometer, promoted by the pressure fluctuations normally present in a fluidized bed system may have significantly influenced the magnitude of deviations.

Figures 5(a) and 5(b) show that results from the mathematical model were closest to those measured in experiments when the solids inventory was5.0 kg and the mixture ratio was 5.0%, especially for the riser and standpipe sections. For the L-valve, the best results were obtained from the mathematical model with the mixture ratio of 2.5% and solids inventory of 3.5 kg. Figures 6(a) and 6(b) suggest that the discrepancy between the experiment and simulations also decreased for the high level of mixture ratio for the regions of the riser, standpipe and L-valve. The opposite occurs in the region of the cyclone.

In order to determine the response capacity of the mathematical model regarding levels variations of mixture ratio and solids inventory, an analysis based on the statistical significance of deviations was carried out. Figure 7 and figure 8 show a comparison of differences found between the results of the mathematical model and experiments for the pressure drops in the riser, cyclone, standpipe and L-valve.

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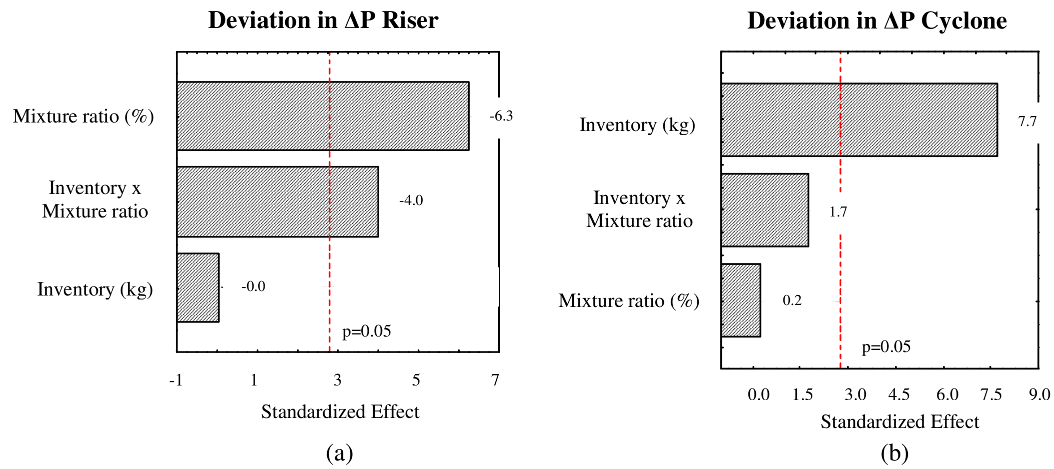

Figure 7– Standardized effect of the deviation shown by the change in level of the different factors in riser and cyclone components.

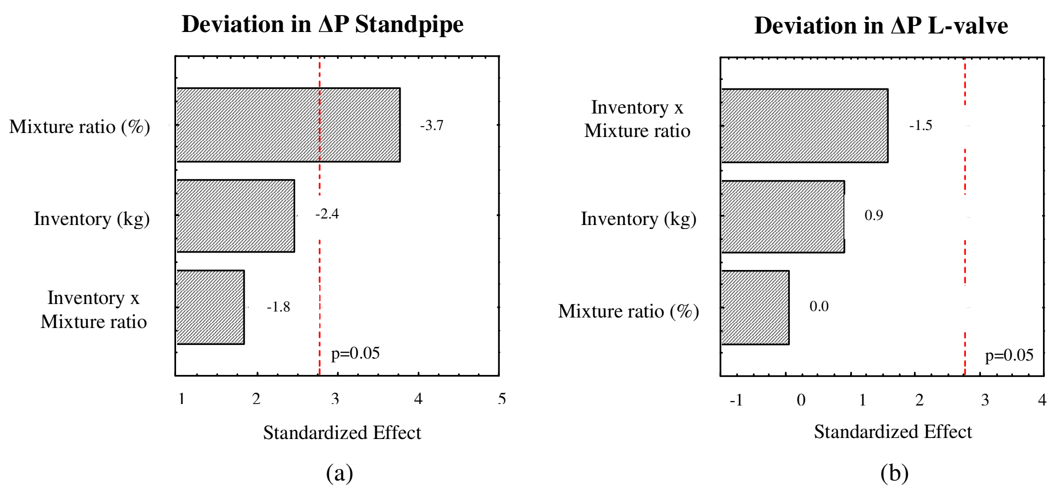

Figure 8– Standardized effect of the deviation shown by the change in level of the different factors in standpipe and L-valve components.

Results indicate that for the riser section the difference between simulation and experiment only associated to the inventory effect is not significant at confidence level of 95%. This suggests that the mathematical model is sensitive to variations of the solids inventory. On the other hand, for the cyclone section, the results show that only the solids inventory caused significant changes in the deviation value. Thus, the mathematical model of the cyclone was less reliable with variations imposed on the solids inventory and indifferent in terms of the mixture ratio level. Another aspect to be realized is that increasing the solids inventory, the deviation had positive signal. This means that there was an increase of deviation between the simulated values and the measured values.

In the case of the standpipe section the mixture ratio was the significant factor, which had less influence on the deviation when the mixture ratio changed from low to high level. In the component, variations in solids inventory levels did not cause a significant deviation.

Finally, for the L-valve region was observed that none of the controlled variables caused significant changes in the value of the deviation between the experimental and simulated by the mathematical model. Such situations suggests that for this component, the model responds satisfactory to changes in the solids inventory and the mixture ratio, keeping almost invariable the deviation values for any tested operating condition. So, taking into account all components of the CFB analyzed in cold fast fluidization regime, the L-valve mathematical sub-model showed the best result because it adapted well to the several operating conditions imposed in the loop.

4. CONCLUSIONS

In this study it was experimentally verified that the static pressure profile in a bench-scale cold circulating fluidized bed system composed of ternary mixture of solids is driven by the pressure balance around the loop. The geometry of the pressure profile is also in concordance with data reported in literature for beds composed by a solid material.

The change in solids inventory from low level to high level, while maintaining the mixture ratio constant revealed an increase in the static pressure at all points of measurements, as expected. Also, with constant solids inventory, and the mixture ratio varying from low level to high level, it was noticed that the effect caused due to drag force in the loop can be significant, especially when the solids inventory was in the high level. In this case, the bed volume increases considerably, enhancing the attrition between solids and walls. In addition, results suggest that the pressure drop in riser, cyclone and standpipe depends mainly on solids inventory at 95% of confidence level confidence. However, in the valve L, none of factors at tested levels caused a significant effect on the pressure drop.

When experimental and simulating results were compared it was found that the deviation in L-valve section is small in all operating conditions, whereas in the cyclone were obtained the largest discrepancies. A sensitive analysis of the mathematical model was done and results showed that the main components of the CFB system respond differently with the controlled factor and its levels. In the standpipe, it was evident that the mixture ratio is the factor with the greatest significance, having a positive influence when proportionally more fuel particles are added in the bed. On the other hand, the deviation in the L-valve was not affected by the level changes in both factors, which showed that the mathematical model adopted better for this component.

The technique of design of experiments constituted an important tool to verify the behavior of relatively complex phenomena without performing many tests, saving time and resources, especially for the operation of equipment built in bench or pilot scale. The results obtained through the mathematical model were satisfactory for most components of the CFB system, mainly when it worked in high level of mixture ratio, requiring only some adjustments that can be done by including new correlations obtained from further experimental tests.

5. ACKNOWLEDGEMENTS

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