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PARAMETRIC APPROACH ABOUT FLUIDIZED BED OF PARTICLES OF SILICA AND CASHEW NUT SHELL

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Abstract. *Gaseous fluidization of solid particles arises as an alternative technology to gasify the cashew nut shell (CNS) efficiently. However, still there are fluid dynamic phenomena to be known when a heterogeneous medium is fluidized and, also, little information about this kind of biomass is available. Therefore, an experimental study on fluidization of bed constituted of particles of silica and CNS was performed in order to achieve an encompassing understanding about the phenomena of the fluidization process, targeting to obtain project parameters necessary to the development of an efficient CNS gasifier. Thus, this investigation aims to learn about wall effects, flow profile, pressure variation, and CNS particle displacement velocity along the fluidized column. The experimental apparatus is constituted of three acrylic tubes with internal diameters of approximately 45, 70 and 90 mm, and 1-meter long, where pressure drops were measured by piezo-resistive sensor. Besides varying column diameters, different granulometries of silica particles (72.43 µm, 321.02 µm and 546.61 µm) were experimented on this study, utilizing different CNS particle sizes. The bubbly regime was applied to gas flow in the fluidized bed and effects of flow on the bed were studied, in order to determine the best region of the column for the biomass injection. It was possible to observe the formation tendency of "silica piston" along the fluidized column. As this phenomenon tends to interrupt the gas flow, some experiments were performed to identify the limit-dimensions of column, concerning the length-diameter ratio.*

Keywords: *Fluidized bed,* cashew nut shell, *gasification.*

1. INTRODUCTION

The environmental impact caused by the great amount of cashew nut shell (CNS), disposed on soils and rivers without any criterion, has been the main motivation for this experimental investigation. Substituting the fossil fuels, some companies have reused this biomass through the direct burning in furnace of hybrid boilers in order to diminish their operational costs. However, they have faced other maintenance expenses associated to the deposits of soot and carbonized organic substances on firebox walls. Besides, combustion of this relatively complex biomass, without laboratory studies, has resulted in high emission indices of particulate material and toxic gases, which are still not well known. Practical data from those companies have pointed out the strong corrosive effects of gases resulting from the combustion process in conventional furnaces, which can put in risk the facility structures.

Basically, CNS is the outer skin of cashew kernel containing about 25% of tannin material and 11% of non-tannin material, which has properties similar to that of imported wattle bark tannin used in leather industry (Singh et al., 2006). The Cashew nut has a shell of about 1/8 inch thickness, with a soft honeycomb structure inside, containing a dark brown viscous liquid. It is called CNSL, which is pericarp Guid of the cashew nut (Das and Ganesh, 2003). Typically, the composition of Technical CNSL is approximately 52% cardanol, 10% cardol, and 30% polymeric material, with the remainder being made up of other substances (Das et al., 2004). The Technical CNSL is often further processed by distillation at reduced pressure to remove the polymeric material. The composition of the distilled Technical CNSL is about 78% cardanol, 8% cardol, and 2% polymeric material and the remaining other substances. It should be highlighted that there is technical information about CNSL a lot, including about chemical composition and elementary analysis, however it is very difficult to obtain chemical and physical property data about CNS, specifically.

In order to achieve realistic results from this experimental investigation, CNS samples were obtained from a great company, placed in Ceara – Brazil, which is one of leaderships in the international market of commercialization of cashew nut. An amount of CNS was received from them after drying in oven at 380 K for 3 h, followed of gradual temperature increases up to reach 500 K, approximately, and keeping it for 2 h at each temperature level. In principle, the CNS samples that were received to be applied to this study can be considered relatively dried, although some residual liquid (CNSL) always remains inside the skin.

Then, the principal goal of this research is to apply this biomass cracked in small particles to be fluidized in a silica bed in order to learn about the effects of size of the CNS particles and its chemical and physical properties on bed behavior in terms of pressure drops, flow stream profile, biomass displacement velocity in the column and others process parameters that might affect the combustion process in a gasifier. Recent inventory about an available fluidized bed bibliography involving CNS has demonstrated that the bed fluidization dynamic still needs to better studied theoretical and experimental, even though there are a lot of papers about this issue. However, it is possible to affirm that no investigation has been performed about CNS.

Most of fundamentals about fluidized bed are, in the moment, well diffused academically, however the concepts were structured from some investigations in the 60s, when the development basis of this technology was established. For instance, Werther and Molerus (1973a,b) provided experimental results about gaseous fluidization of solid particles, which have served as reference for others researches in this engineering area, until now. Among their initial scientific contributions, it is possible to highlight: i) Determination of parameters characterizing the local state of fluidization in beds of arbitrary sizes, based on a statistical analysis of the signal, the mean bubble pulse duration, the number of bubbles striking the probe per unit time and the local mean bubble rise velocity; ii) Definition about the spatial distribution of bubbles in gas fluidized beds through bed diameter variation, indicating the characteristic flow profile about the increasing bubble phase near to the wall. Later, Grace and Sun (1991) showed the importance of particle size distribution (PSD) in fluidized beds. Broadening the PSD affects gas flow through the dense phase, produces smaller bubbles, leads to more particles in the dilute phase and causes earlier transition to the turbulent hydrodynamic regime of fluidization. Chemical conversion is therefore enhanced by broadening the PSD, and the enhancement increases when the bed operates in the turbulent regime. Ghaly and Ergudenler (1993) studied the agglomeration characteristics of alumina sand in a fluidized bed straw gasification system at various equivalence ratios. They could identify that the ash content and temperature had influence on the agglomeration of alumina sand and, also, they learned that the higher the ash content and/or the temperature the stronger was the bonding. In this context, Barea and Leckner (2010) have begun an important theoretical investigation in terms of modeling of biomass gasification in bubbling and circulating fluidized bed gasifiers. They have attempted approaches to model the process, from black-box models to computational fluid-dynamic models, where semi-empirical correlations were used to simplify the fluid-dynamics.

However, still based on the researched literature, it is possible to comment that the most of experimental or theoretical works about fluidized bed with biomass treats of combustion/gasification directly, with little investigation about fluid dynamic features concerning the gas flowing into a totally heterogeneous medium, formed by the air-biomass-silica as well as residual particles from the combustion products together. So, it is still difficult to have a whole idea about the phenomena present on fluidized bed, and it is not easy to perform an analytic or numerical modeling to explain the process in an integral way. Therefore, the present paper aims to present the results obtained experimentally about the gaseous fluidization of a bed constituted of silica and CNS particles. In principle, the presence of the biomass in the sand column results in global and local alterations of density, gas flow velocity, bubble distribution, pressures drops, etc.. Then, that can generate changes of process behavior that affect the combustion efficiency and stability, considering that this investigation should be important to help developing a gasifier dedicate to CNS.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

The development of a fluidized bed reactor with silica sand is based on parameters that define the conditions for its operation, such as ideal diameter and height of column, minimum fluidization velocity, flow gas, pressure drops, appropriate point for insertion of biomass and optimum particle diameter, among others. Obtaining these parameters depends on analysis of experimental results about fluid dynamic phenomena in laboratory conditions.

The experimental apparatus utilized in this investigation consists of three columns of silica bed in side acrylic tubes as shown at Figure 1. The fluid dynamic behavior of the bed was studied through these three acrylic tubes, in which all have similar geometry, i.e., wall thickness of 0.005 m and height of 1.00 m. They are differentiated only by their internal diameters, with the following measures: 0.044 m, 0.069 m and 0.090 m. The tubes were assembled on a metal structure, assuring leveling of them. As shown in this figure, at the bottom section of experimental study setup, there is an injection system of the working fluid (air) that supplies individually each tube with same operation conditions, i.e., the monitoring instrument and accessory maintains regular pressure, temperature, cleaning, humidity and supply stability for all experiments. Then, the compressed air is supplied after a pressure regulator, with filtrating system, which maintains the pressure close to 100 psi. The air flow is assured by a manifold that receives it from pressure regulator and stands connected to each bottom section of acrylic tube.

Basically, the bottom section that supports the acrylic tube is a kind of air distributor with tapered internal geometry (in cone shape), made of nylon. Through this distributor, air is supplied to be blown to the silica bed, passing through a grid frame that bears the sand column and allows the air flow toward the top section of study setup. This frame (a set of screen) is made of stainless steel and has small bores of approximately 230 meshes. It is placed exactly in the bed basis, i.e., at the 0.0-m level of the acrylic tube. These screens, fixed at the bottom, prevent the passage of very small grains of silica or CNS from the column basis to the air supply chamber, bellow the frame. At the top section of each tube filters are installed to retain dust of sand or CNS that was pulled out from the bed. The gases from the column are connected to the exhaust.

Nº DO ITEM	Nº DA PEÇA	QTD.
1	Plennum	1
2	Anel	1
3	Tela	1
4	kistler	1
5	Tubo de Cobre	1
6	Vedação	1
7	Tubo de acrilico	1

Figure 1: Drawing of components of the experimental apparatus

The operation of the experimental apparatus had to be performed with a lot worry about pressure fluctuation in the air pipeline. Therefore, a air reservoir was installed between the compressor/pressure regulator and the study setup in order to cushion the pressure waves from pipeline of air. Other cares were taken about possible pressure waves between the silica column and manometers, e.g., a manifold with regulating valves was installed between both the ends to also work as attenuation cushion. About the pressure control of air line, a gauge analog control was employed in the system, so that, for varying the air flow into the bed two flowmeters measuring range from 7.8658E-6 to 7.8658E-5 m^3/s were installed.

For the purpose of measuring the pressure at various points along the length of the bed, eight points were selected as pressure raise in each tube, from the bottom to the top section. So, the column was divided into equidistant points, i.e., 0.05 m from each other, beginning at level 0.10 m in relation to the bed basis. The bed pressure outlets were connected to 8 gauges of the U type with water column, measuring range from 0 to 1000 mm H_2O. To measure the pressure at the base of the bed, sensitive pressure gauge was installed to capture the pressure in the dimension 0.0 m. The purpose of this apparatus is to compare the behavior of the bed when it varies height, pressure, fluidization velocity, particle size and adding the biomass bed. The Figure 2 shows the full set of apparatuses used for the present study.

About fluid dynamic phenomena, the test apparatus allowed analyzing the behavior of the bed, firstly, with silica sand in the particle sizes of 546.611 mm, 321.023 mm, and 72.432 mm. The column height of the bed were stated to study 0,075 m, 0,125 m, 0,175 m, 0,225 m, 0,275 m, 0,325 m, 0,375 m, 0,425 I 0,475 m. The experimental procedure begins with some test definitions: i) weighing of certain quantity of sand enough to fill the volume stipulated for a given study dimension; ii) choice the particle size of sand and/or CNS; iii) compactation of the sand mass sand, gently tapping in the column; iv) gradual open of the flow regulanting valve; v) record of pressure and bed height variations, until full fluidizing the bed, smoothly, so that no particle is taken out from the bed; vi) record of the flowmeter and gauge data, after gas flow reaching its maximum pressure value and get points that identify pressure drop profile gradually; vii) record of the same data in downward operation; and viii) record of the final height of the bed. Finally, this procedure is repeated for the binary bed, in which CNS particle size ranges between14-20 and 20-45 meshes.

2.1 Instruments

A number of parameters are monitored during the operation the experimental apparatus, such as temperature; inlet and outlet pressure at the top and bottom sections, besides the pressure drops along the silica column. The temperature inside the porous medium is measured through thermocouples of the K type. The pressures were measured in several points of the study setup, in the following way: i) the pressure at the bed basis was utilized a piezo-resistive sensor (model Kistler), capable to measures accurately from vacuum to 1 MPa; ii) the pressures at all the points along the column, in order to identify the gradual pressure drops from the bottom to the top section, were measured through manometers of the U type. All of the manometers were calibrated through the piezo-resistive sensor. For all the instruments applied to this study details about their uncertainties were analyzed, as it is commented in this following: i) Temperature of the exhaust gases (or inlet gases): Two K-type thermocouple, featured with a fine tip and presenting an error of 0.75% for the full scale; ii) Gases Flowrate: Rotameters with 7% FS-accuracy, with calibration by comparison of their readings to the ones from two primary standard instruments. Using the calibration table to fit the readings, the error of the (corrected) measurements is supposedly reduced to the repeatability of the rotameters (~1%-FS) plus the error of the primary standard instruments (~1%-FS); iii) Pressure Signal: Frequency transducer - Utilizing a 10-V power supply, it yields square wave pulse outputs, in which its precision linearity is approximately of ±1.5% of full scale. Based on the accuracy of these instruments utilized on the experimental apparatus, the uncertainties of the pressure, gas flow and temperature were estimated in ±0.8%, ±3.5% and ±5.4%, respectively.

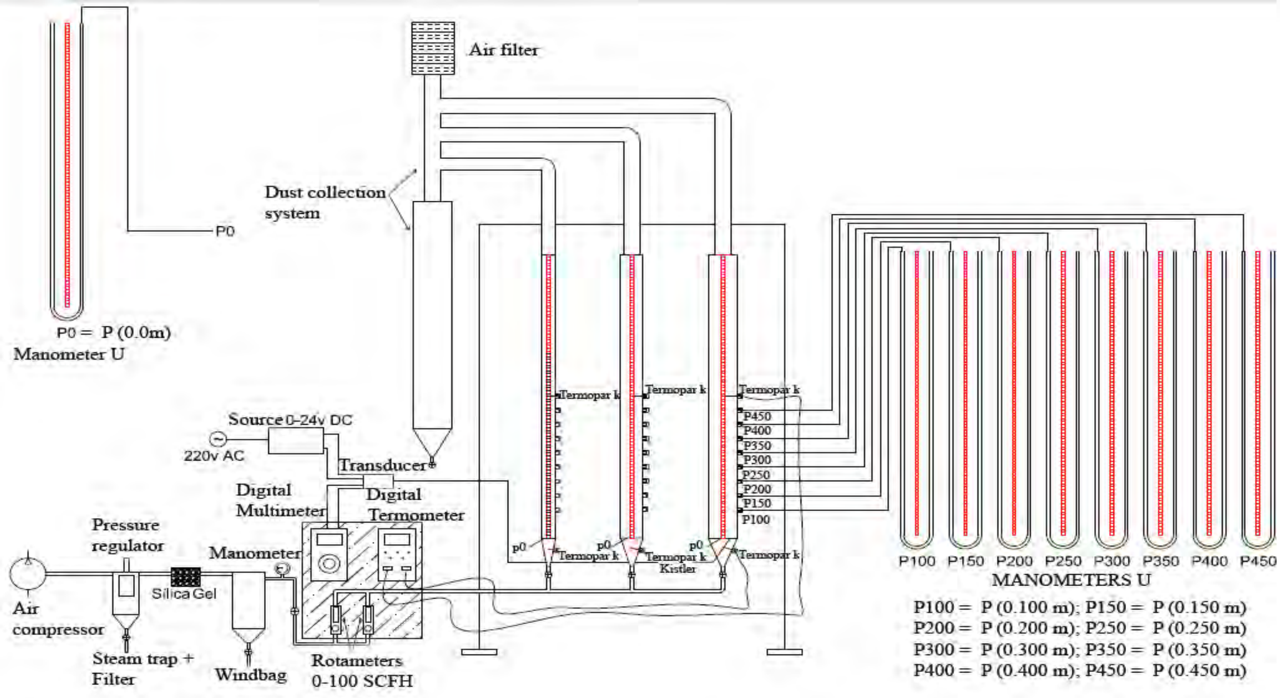


Figure 2: General arrangement of monitoring instruments of the experimental apparatus

3. FLUID DYNAMIC FEATURES

3.1 Pressure reduction and minimum fluidization velocity

According to Geldart (1976) the value of pressure reduction depends on the mass contained in the bed and cross section of the tube.

$$\Delta P = \frac{0,1M}{A} \tag{1}$$

Where ΔP is a pressure reduction in the bed, M is mass making up the bed, A is cross sectional area of tube.

This parameter used as theoretical calculations to errors compared with experimental values. For the minimum fluidization velocity determined by the Ergun equation simplified.

$$\mu_{mf} = \frac{g(\rho_s - \rho_f)d_p{}^2\phi^2\varepsilon_{mf}{}^3}{150\mu(1-\varepsilon_{mf})} \tag{2}$$

Where g is local acceleration of gravity, ρ_s, ρ_f are the bed surface densities and of working fluid, d_p is the particle diameter, ε_{mf} is porosity of the bed material under conditions of minimum fluidization, ϕ is a sphericity the particular bed which is formed.

3.2 Equation of regime the bed particle silica

It is important to make sure in which of the states of fluidization system is to validate the calculations according to the equation Wilhelm and Kwauk (1948) in Kunii and Levenspiel (1979) through the Froude number,

$$Fr_{mf} = \frac{\mu_{mf}{}^2}{d_p g} \tag{3}$$

If Fr_{mf} < 0.13 – uniform fluidization and, if Fr_{mf} > 0.13 – bubbling fluidization;

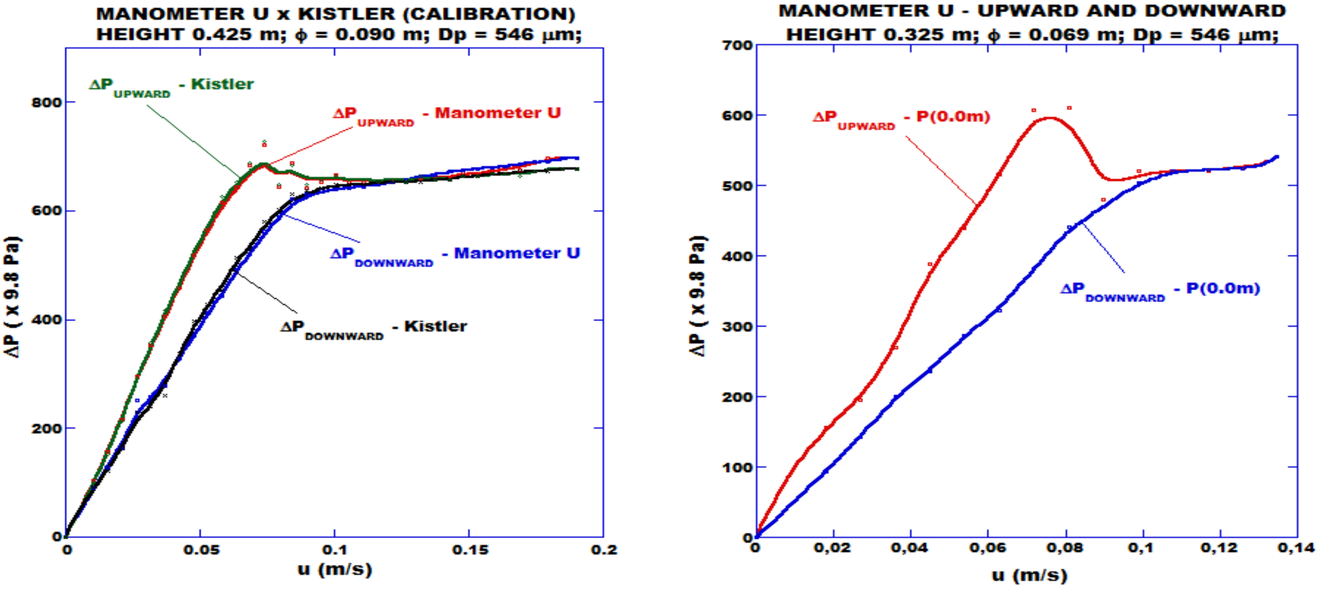
Romero and Johnson (1962) have suggested four dimensionless groups to characterize the quality of fluidization: The Froude number Fr_{mf} , the Reynolds number at minimum fluidi dynamics (Re_{mf}),the number of equivalent length and the volume mass of the bed at minimum fluidi dynamics, the ratio for the length of the bed diameter.

4. RESULTS AND DISCUSSIONS

In this study, the pressure variation in relation to the gas flow applied to experiments was analyzed in terms of characterization of pressure distribution profile that can represent the fluidization phenomena of the column, in reasonably realistic way. Thereby, the pressure disturbances at the basis and along the bed were set on graphs as well as the influences of biomass particle dimension, silica grain size and acrylic tube diameter variations on pressure profile had to interpreted and adjusted properly. Therefore, the biomass insertion method and concentration in the silica bed and, also, biomass particle sizes were studied as parameters that affect both flow and pressure drop in the column. It should be highlighted that the biomass contents in relation the mass quantity of the silica bed applied to the experiments were 0; 2.8; and 3.9%. The column constituted of silica and biomass particles was considered as binary bed, in which the biomass presence affects principally the global density of the bed and, hence, the pressures drop and fluidization velocity. Additionally, there is influence of the biomass concentration on the expansion index of the bed as well as on the diffusion process of own biomass in the bed, which could have consequences on the gasification.

The following graphs show the pressure profile of the bed of silica particles. As it was commented in before section, the pressure reading was obtained by a pressure gauge installed in the U-base of the bed, that is, at the level of the screen which supports the bed of particulate silica (dimension 0.0 mm). The graphics the pressure drop versus flow velocity characterize the behavior of the bed in terms of the influences of increases of pressure and flow velocity on the bed fluidization. The experiments were performed for three different tube diameters (0.044 m; 0.069 m; 0.090 m) and average silica particle (546 μm; 321 μm; and 72 μm).

4.1 Pressure gauge calibration



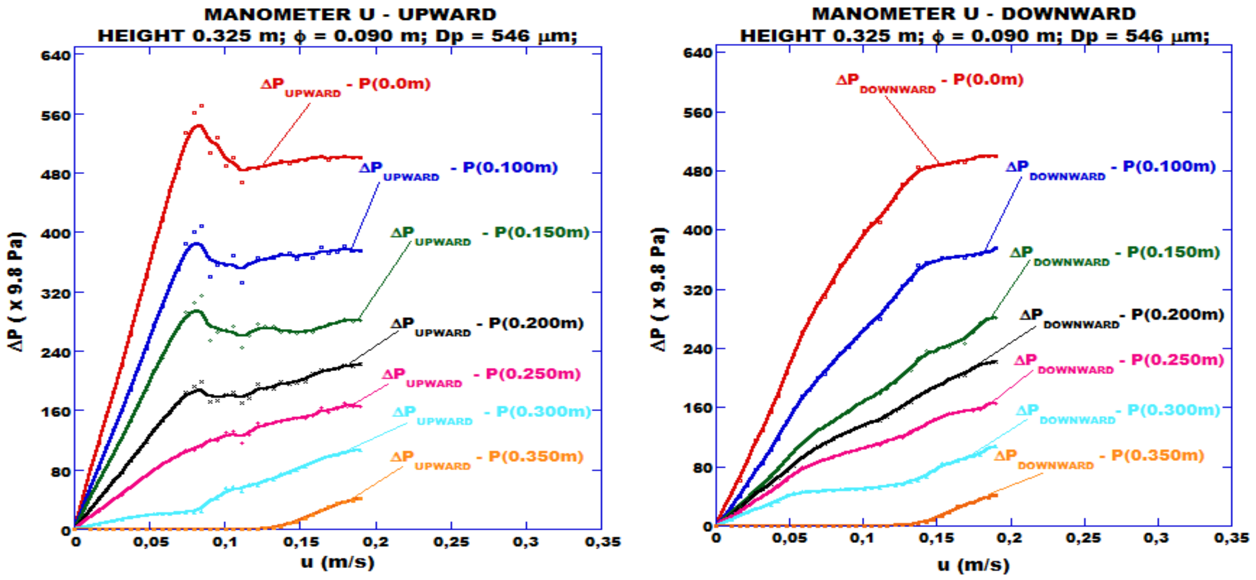
(a) (b)

Figure 3: (a) Graph of ΔP x u (height = 0.425 m; sand diameter of 546 μm; and tube diameter of 0.090 m)
(b) Graph of ΔP x u (height = 0.325 m; sand diameter of 546 μm; and tube diameter of 0.069 m)

Figure 3 (a,b) aims to show typical pressure profiles of fluidization, in which the red (upward) and blue (downward) represent pressure data obtained with piezo-resistive sensor and manometer of the U type. Figure 3a demonstrates that manometer of U type could be calibrated properly. It should mention that both the experiments were performed with acrylic tubes filled with only silica sand. Based on this figure there is influence of tube diameter on pressure profile.

4.2 Pressure drops along the column

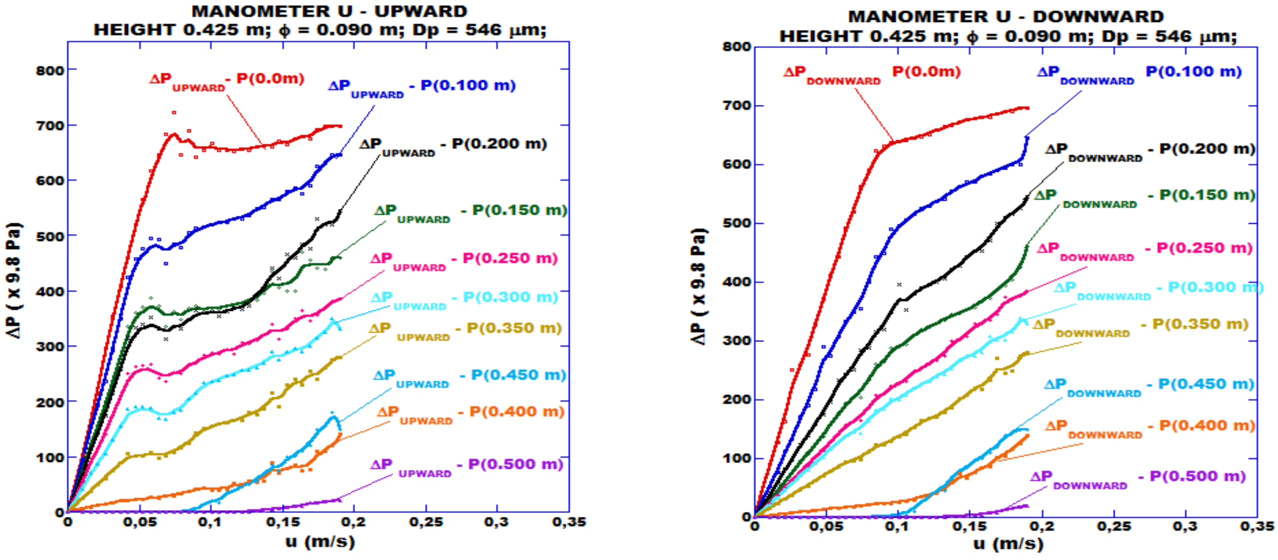
The graphs of Figure 4 (a,b) show the variation of pressure along the column. P (0.0m) denotes the pressure reading at the base, while P (0.100 m) denotes the pressure measured on the side of the bed, at the height of 0.100 m above the screen support (base). Likewise P (0.150 m), P (0.200 m), P (0.250 m), P (0.300 m), P (0.350 m), P (0.400 m), P (0.450 m), P (0.500 m) denote the pressure readings obtained on the side of the pipe at the respective heights. It should be noted that as the pressure reading is obtained at more distant position in relation to the base the pressure peak in the profile becomes more attenuated.



(a) (b)

Figure 4: (a) Graph of ΔP x u (Upward; height = 0.325 m; sand diameter of 546 μm; and tube diameter of 0.090 m)
(b) Graph of ΔP x u (Downward; height = 0.325 m; sand diameter of 546 μm; and tube diameter of 0.090 m)

Figure 5 (a.b) shows the graph of the pressure drop profile in relation the gas flow velocity, measured along the fluidized bed in both the directions, upward and downward, i.e., the differential pressure when there is increase or decrease in the gas velocity, respectively. Most experiments behaved similarly to the graphs of Figures 5 (a) and 5 (b) where a pressure drop occurs across the bed, as it increases the level where the measurement is performed with pressure gauge in U. Also for other diameters (0.069 and 0.044 m) and different granulometry (321 μm) of those shown in Figures 5 (a) and 5 (b), the behavior was similar.



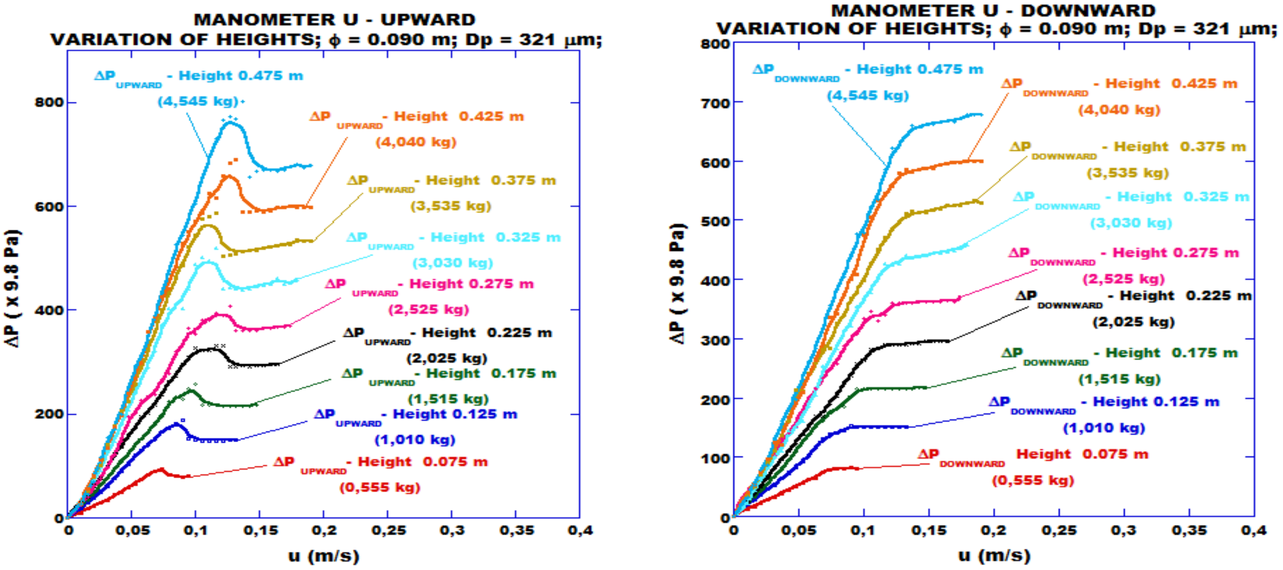
(a) (b)

Figure 5: (a) Graph of ΔP x u (Upward; height = 0.425 m; sand diameter of 546 μm; and tube diameter of 0.090 m)
(b) Graph of ΔP x u (Downward; height = 0.425 m; sand diameter of 546 μm; and tube diameter of 0.090 m)

Figure 5 aims to demonstrate that there are instability zone where the pressure drop is inverted along the column. These phenomena suggest that these regions should be selected to perform the biomass insertion in the silica bed. There a tendency of vortex formation in the gas flow and bubble concentration at these points of the column. However, at the up position above in which this phenomenon takes place the biomass displacement can be interrupted, so that, the combustion process could be affected significantly.

4.3 Influence of column height

The graphs of Figure 6 (a,b) show pressure drop profiles, measured at the base of the bed (0.0 m), in which the quantity of sand deposited on the acrylic tube is increased that correspond to different bed heights. From these graphs it is possible conclude that the increase in mass quantity of silica, i.e., an increase in bed height, causes an increase of pressure values measured at the base of the fluidized bed, becoming more defined the pressure peaks in profiles.

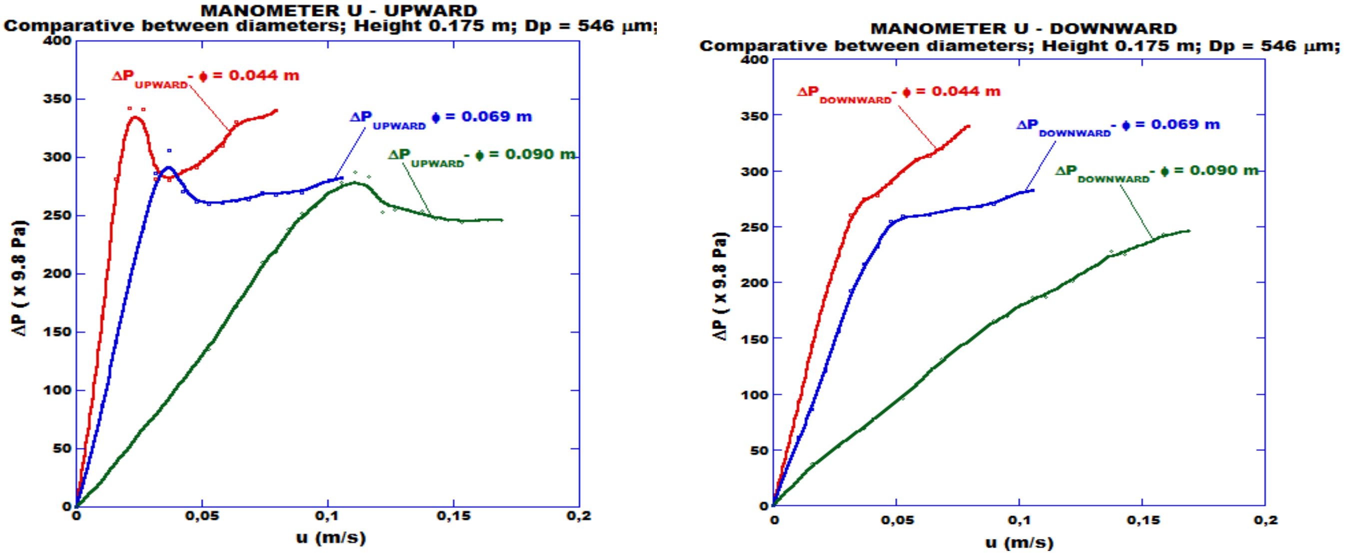


(a) (b)

Figure 5: (a) Graph of ΔP x u (Upward; height = 0.425 m; sand diameter of 546 μm; and tube diameter of 0.090 m)
(b) Graph of ΔP x u (Downward; height = 0.425 m; sand diameter of 546 μm; and tube diameter of 0.090 m)

4.4 Influence of tube diameter

The graphs of Figure 6 (a,b) show the pressure drop values obtained at the base of the bed for a tube with different diameters (0.044 m, 0.069, and 0.090 m). This figure allows analyzing the influence of the diameter on the pressure drop profile, i.e., fluid-dynamic effects due to the wall on the gas flow and, hence, on the pressure drop profile, measured at the base of the column (0.0m). Based on Darcy's law, the inclination of the straight line of pressure drop profile increase as tube diameter is reduced, due to friction effects on the gas flow and, hence, on the bed movement.



(a) (b)

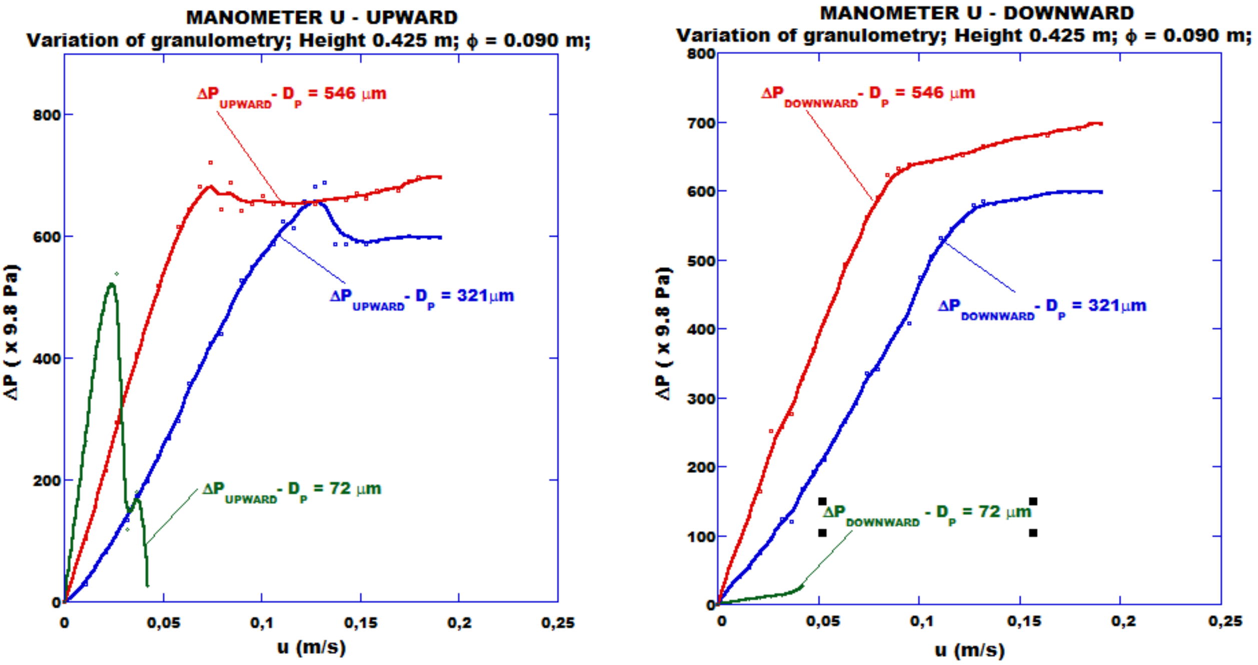
Figure 6: (a) Upward and (b) Downward - Graphs of ΔP x u for three tube diameters: 0.044 m, 0.069 m, and 0.090 m

4.5 Influence of silica particle size

The graphs of Figure 7 (a,b) show the pressure drop values measured at the base of the silica bed (0.0 m), where sand grain sizes (Dp) were varied considerably. The average diameters of particles applied to experiments were the following: 546 μm, 321 μm, and 72 μm, in which the pressure drops were measured at the base of the column.

It should be highlighted that the curves ―pressure drop versus gas velocity” for the average particle diameter of 72 μm there was non-known phenomena in fluidization processes. There is tendency to form a kind of ―sand piston” when the flow velocity is increased, forming a relative big bubble in certain position of the bed close to its base, in which the gas flow is interrupted completely, so that, this big bubble gets bigger and push up the send column above as a compact material.

This phenomenon is very interesting, and until amazing, because if compare the fluidization of the beds constituted by grains with 546 μm and 321 μm, it is possible to realize that lower diameter size favor the fluidization process. Nevertheless, when the silica sand particle diameter is too small, it is supposed that there is a tendency to compact extremely the material of the bed, reducing the porosity of the column.



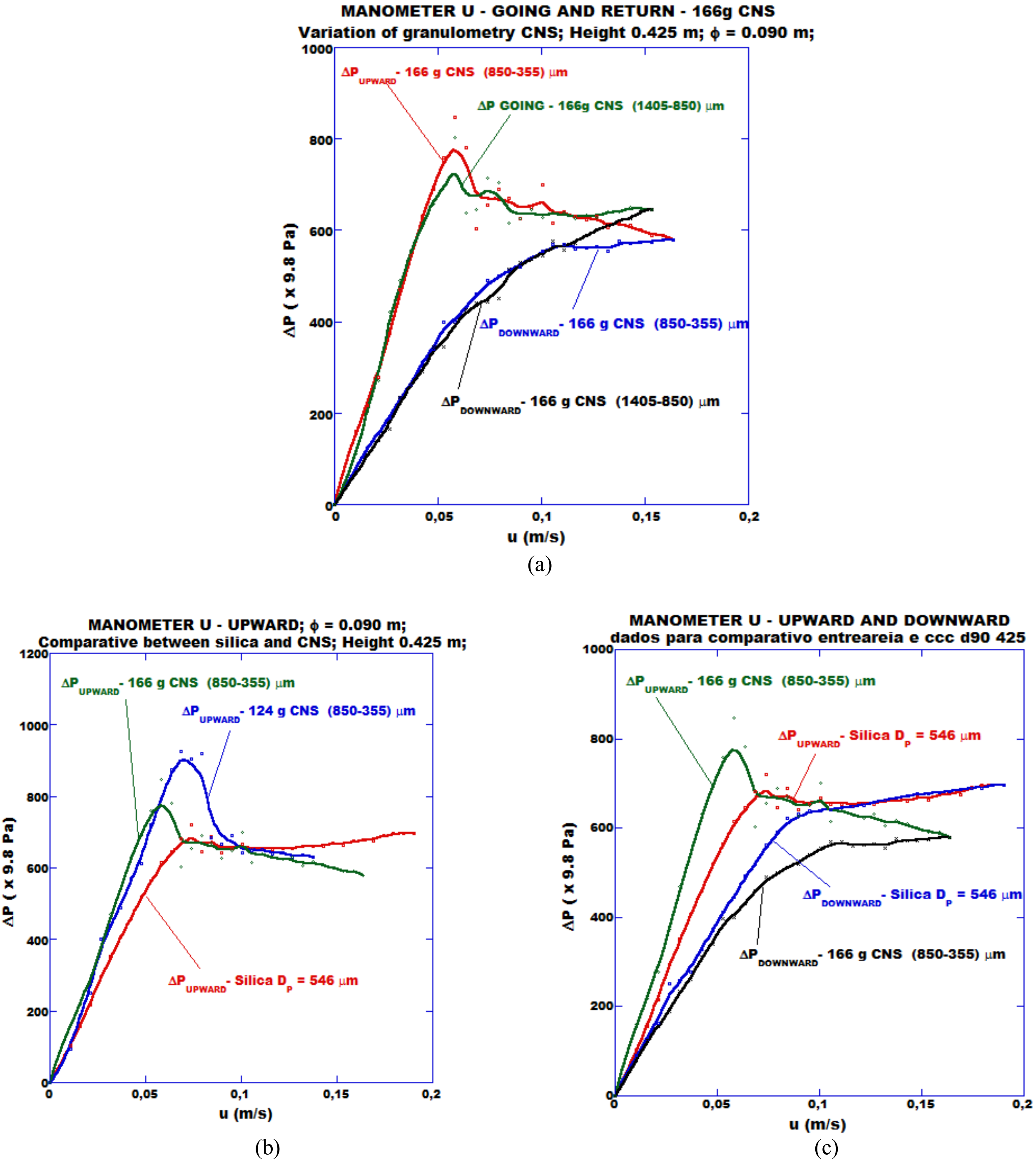
(a) (b)

Figure 7: Effects of variation of granulometry on pressure drop profile - (a) Upward and (b) Downward.

4.6 Influence of concentration and size of biomass particle

The graphs of Figure 8 show the experimental results about fluidization of bed formed by particles of silica and biomass (CNS), that is, a binary bed. In this study a mixture of silica and CNS was varied to obtain specific concentrations of CNS 0%, 2.8% and 3.8% relative to the total weight of sand. These concentrations were calculated with base on the value of air-fuel ratio suggested by Figueiredo (   ) to burn completely all the biomass, i.e., calculation to reach the stoichiometry for combustion of the CNS in a conventional reactor. In reality, the presence of a porous medium (silica) inside the reactor (or gasifier) the heat transfer phenomena are changed considerably that could justify more amount of air in the mixture with the fuel (CNS).

However, as commented before, no experimental investigation has been performed concerning this kind of biomass burning in fluidized bed. Thus, the biomass concentration value and the air flow rates studied to provide a satisfactory transport of biomass along the bed were calculated, reaching the the following concentrations: 2.8 and 3.8%, based on the quantity of sand inside of the acrylic tube. These tests were carried out with the tube diameter of 0.090 m, with average silica particle diameter of 546 μm for 0.425-m level in relation to base of the bed. The granulometry of the CNS was varied to understand the influence of the fluidizing gas in this binary mixture (silica and biomass). The particle sizes were used: ASTM 20-45 (850-355 μm) and ASTM 14-20 (1405-850 μm.)



(a)

(b)

(c)

Figure 8: (a) Variation of the particle size of the CNS in the bed to the concentration of 3.9% (upward and downward);
(b) Comparison of the effects of particle size in the bed for the same quota (upward);
(c) Comparison of the effects of particle size in the bed to about the same height (upward and downward)

5. CONCLUSIONS

With this study were obtained parameters that can support the development of a fluidized bed reactor for gasification of CNS. From this experimental investigation some conclusions can enunciated, such as:

- About the variation of pressure, it was found that the profiles represent the fluid dynamic phenomena in the bed. As the flow rate increased, the pressure of the bed tends to increase up to a point where the fluidized bed and, then, the pressure falls and remains approximately constant;
- About the variation of the dimension of the bed (height), it is supposed that the pressure curve was shifted because of the increased weight on the tube base that hinders the passage of air, slowing fluidization;

- About changes in the tube diameter, it was verified that this parameter affects the pressure significantly, because when the distribution area of the air in the tube base is increased, this facilitates the sand to be pushed by decreasing pressure values in the base of the bed;
- About the influence of the biomass insertion into the bed with gas flow on regime, it is possible to mention that the physical-chemical properties of CNS are quite different from the silica particles that can changing entirely the pressure drop profile in the bed in relation to it containing sand only. It was concluded that the ideal point to enter the shell of cashew nuts in the bed is exactly where the pressure inversion occurs, shown in Figure 5;
- About the use of different particle diameters, for both CNS as sand, the results have shown that the particle size influences greatly the pressure variation by changing the flow regime. The smaller particles occupy spaces that cannot be occupied by the larger diameter, causing a greater compression of the bed hindering the passage of air.

6. ACKNOWLEDGEMENTS

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