FLUIDIZATION OF BINARY MIXTURES OF COAL WITH SAND AND BIOMASS IN A BENCH SCALE REACTOR

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ABSTRACT

Thermal energy conversion industries have been increasingly employing fluidized bed combustion technology. Fluidized beds are a good choice to burn low rank coals, biomass and fuels with high moisture content, such as industrial and urban waste. The fluid dynamics of a fluidized bed provides valuable information for the design and operation of such system. However, the mathematical modeling of fluidization, even for homogeneous particles, is a complex subject. It comprises modeling the gas flow, the solids flow and the interaction of them. In the case of mixtures of particles with different physical properties, predicting fluid dynamics is a major challenge. It is common to rely on empirical correlations in order to obtain design parameters such as fluidization velocity and bed expansion rate. The objective of the present work is to investigate the fluidization behavior of blends of coal with two lignocellulosic biomasses and with an inert material. The fluidization velocities obtained experimentally were compared with predictions using correlations, and features such as segregation and agglomeration of clusters during the experiments have been studied. The materials employed in the blends with coal were sand and sugarcane bagasse and straw, in the following proportions: 20, 40, 60 and 80 percent in volume. Coal, sand and biomasses were analyzed for their particle size, mass density and bulk density, and biomasses also for their proximate and ultimate elemental composition, heating value and thermo gravimetric behavior (TGA). A bench scale reactor was employed to fluidize coal, sand, and blends of coal-sand and coal-biomasses. The fluidized bed was a cylindrical tube of 94 mm ID. The fluidization agent was compressed air at ambient temperature, injected through a mesh distributor at the bottom of the reactor. A differential pressure transmitter (Novus Huba 699) was employed to measure pressure drop along the fluidized bed, while the air flow rate was measured by a flow rate meter (IFM SD6050). The characterization showed that the biomasses present similar proximate and elemental compositions. The heating values found were 17.1 MJ/kg for sugarcane bagasse, 17.4 MJ/kg for sugarcane straw and 19 MJ/kg for coal. The mass densities varied between 1002 kg/m³ for sugarcane straw and 2587 g/cm³ for sand. The mean particle size varied between 931 µm for sugarcane straw and 363 µm for sand. The TGA showed close results for the biomasses, with the most intense degradation of the samples between 200 and 400 ºC. Fluidization tests showed minimum fluidization velocities of about 0.58 m/s for coal and 0.14 m/s for sand, and velocities between 0.16 and 0.28 m/s for coal and sand blends. The tests showed that the coal and sand mixtures fluidized well in any proportion. Blends of coal and biomass, however, fluidized well in proportions up to 60 percent in volume of biomass. For proportions above this limit, it was verified the formation of preferential paths and severe agglomeration of clusters in the bed. The correlations used were able to predict the minimum fluidization velocity for inert materials, for coal and sand mixtures and for mixtures with up to 40% of biomass volume content.

Key-words: Fluidization. Coal. Binary mixtures. Biomass. Sand.

RESUMO

As plantas de conversão de energia térmica têm empregado cada vez mais a tecnologia de combustão em leito fluidizado. Os leitos fluidizados são uma boa escolha para queimar carvões de baixo rank, biomassas e combustíveis de alta umidade, como resíduos industriais e urbanos. A dinâmica de fluidos de um leito fluidizado fornece informações valiosas para a concepção e operação desses sistemas. No entanto, a modelagem matemática da fluidização, mesmo para partículas homogêneas, é um assunto complexo. Compreende modelar o fluxo do gás, o fluxo dos sólidos e a interação entre eles. No caso de misturas de partículas com diferentes propriedades físicas, prever a dinâmica dos fluidos é um grande desafio. É comum confiar em correlações empíricas para obter parâmetros de projeto, tais como velocidade de *fluidização e taxa de expansão do leito. O objetivo do presente trabalho é investigar o comportamento de fluidização de misturas de carvão com duas biomassas lignocelulósicas e com um material inerte. As velocidades de fluidização obtidas experimentalmente foram comparadas com as predições utilizando correlações, e foram estudadas características como a segregação e aglomeração no leito durante as experiências. Os materiais empregados nas misturas com carvão foram areia, palha e bagaço de cana-de-açúcar, nas seguintes proporções: 20, 40, 60 e 80 por cento em volume. O carvão, a areia e as biomassas foram analisados quanto ao seu tamanho de partícula, massa específica real e aparente, e as biomassas quanto à sua composição elementar e imediata, poder calorífico e comportamento termogravimétrico (TGA). Um modelo de reator em escala de bancada foi empregado para fluidizar carvão, areia, misturas de carvão e areia e misturas de biomassas e carvão. O leito fluidizado consistiu em um tubo cilíndrico de 94 mm ID. O agente de fluidização foi ar comprimido à temperatura ambiente, injetado através de um distribuidor de no fundo do reator. Utilizou-se um transmissor de pressão diferencial (Novus Huba 699) para medir a queda de pressão ao longo do leito fluidizado, enquanto que a vazão de ar foi medida por um medidor IFM SD6050. A caracterização mostrou que as biomassas apresentam composições elementares e imediatas similares. Os poderes caloríficos encontrados foram de 17,1 MJ/kg para o bagaço, de 17,4 MJ/kg para a palha de cana e 19 MJ/kg para o carvão. As massas específicas reais variaram entre 1002 kg/m³ para a palha de cana e 2587 kg/m³ para a areia. O tamanho médio das partículas variou entre 363 μm* para a areia *e 931 μm* para a palha de cana. *A TGA mostrou resultados próximos para as biomassas, com a degradação mais intensa das amostras entre 200 e 400 ºC. Os testes de fluidização mostraram velocidades de fluidização mínimas de cerca de 0,58 m/s para carvão e 0,14 m/s para areia e velocidades entre 0,16 e 0,28 m/s para carvão e misturas de areia. Os testes mostraram que as misturas de carvão e areia fluidizaram bem em qualquer proporção. As misturas de carvão e biomassa, no entanto, fluidizaram bem em proporções de até 60% em volume de biomassa. Para proporções acima desse limite, verificou-se a formação de caminhos preferenciais e a ocorrência de aglomerações no leito. As correlações utilizadas foram capazes de prever a velocidade mínima de fluidização para os materiais inertes, para as misturas de carvão e areia e para as misturas com até 40% de biomassa em volume.*

Palavras-chave: *Fluidização. Carvão. Misturas binárias. Biomassa. Areia.*

1 INTRODUCTION

Analyzing the growth rate of energy demand on a global scale over the last decades, it is clear that energy consumption has grown at an unsustainable pace, since much of this additional demand has been met by fossil fuel usage (EIA, Energy Information Administration, 2016). And as known, these fossil fuels have great impact on air pollution and global warming. Therefore, it is urgent to encourage and improve the use of renewable energy sources, among which biomass emerges as one of the most relevant and promising in the Brazilian scenario.

In Brazil, among the several biomasses available, the most important are those from agricultural and industrial waste. According to BEN (National Energy Balance, 2016), the share corresponding to biomass in the domestic supply of electric energy is in the order of 7.3%, and in the total primary energy supply this participation is approximately 27.9% (compared to the 39.4% share of oil and 13.5% of natural gas) (BEN, 2016). These values denote the relevance of biomass in the Brazilian energy scenario, and the great potential for increasing these participations.

In the context of the energy utilization, the main advantages in the use of lignocellulosic biomasses are (BRAZ, 2014; LOURENÇO, 2012):

a) Neutral emission of CO_2, due to the carbon cycle and the photosynthetic growth of the plants;

b) Low emissions of SOx and NOx in thermal conversions, due to the low sulfur and nitrogen contents usually found in lignocellulosic biomass;

c) Social and environmental appeal, through the use of waste (which enhances economic viability) and the incentive to generate jobs and economic activity in rural areas.

In this scenario, the cofiring of coal and biomass is a prominent topic, since it has been presented as a promising form of mitigate CO_2 emissions, as the additional costs are relatively minor and a secondary benefit is provided by the increased fuel flexibility. Worldwide, about 150 cofiring plants are in operation (Luschen and Madlener, 2013). Rio Grande do Sul is the main national producer of coal, accounting for about 90% of the Brazilian reserves. Thus, biomass and coal cofiring is an alternative for the continuation of the exploration and use of coal (an activity with great regional economic potential) in a period of transition to a low carbon economy.

In this context, the objectives of this paper are the following:

- to study the fluidization behavior of mixtures of biomass of sugarcane (the most abundant in the world) with coal, as well as that of coal and sand mixtures;

- compare experimental fluidization velocities with values obtained by correlations found in the literature, evaluating the applicability of these correlations;
- evaluate the behavior of the bed in the fluidization of coal and biomass mixtures, identifying undesirable conditions, such as the formation of preferred paths and clusters.

In general, the increase in the share of renewable energy in the global energy matrix depends on the economic viability of its employment. This feasibility, in turn, depends on the understanding of the potential of use of certain biomasses in the applications of interest, such as cofiring with coal, and, consequently, studies such as the fluid dynamics behavior of these materials. Therefore, it is necessary to investigate the ideal fluidization conditions of biomass and coal binary mixtures, such as ideal mass fractions in the mixture, the characteristic velocities and the bed operating regime. It is expected that the present work will make an important contribution to the feasibility of the use of biomass as renewable energy sources in applications of cofiring with coal.

2 MATERIALS AND METHODS

2.1 PREPARATION AND CHARACTERIZATION OF SAMPLES

All the analyzed biomass were received in natura, and to allow their fluidization and characterization, they were dried in a kiln and ground. The samples were dried at 105 °C for 8 hours. The mill used was a knifes type, model SEIBT MGHS 270A. The final aspect of the prepared samples is shown in Figure 1.

The sand used in the fluidization tests is a commercial material, available from hardware stores. The sand was sieved according to the ISO 3310-1 standard. In order to guarantee a more homogeneous material, only the material from the sieves with the largest mass fraction retained was used, between the mesh 40 and 70.

The mass density of the samples was obtained using a helium pycnometer, model Micrometics AccuPyc II 1340. This equipment has an accuracy of ± 0.02%. The bulk density was obtained using a vessel of known volume and a precision digital scale, with a resolution of 0.002 g.

Figure 1 - Sugarcane bagasse (a) and straw (b) samples

(a) (b)

The mean particle size of the samples was determined by means of a particle size analysis using a set of sieves with a standard aperture following ISO 3310-1.

The measurement of the upper heating value of the materials was performed using an IKA C200 calorimeter. The reference standard for this test was ISO 1928:2009. The tests were performed in duplicate, and the final value was calculated by simple arithmetic mean. The instrument used has a resolution of 1 kJ and a maximum error of 0.1% of the measured value.

2.2 MIXTURES

To perform the fluidization tests with mixtures between coal and sugarcane bagasse, coal and sugarcane straw and coal and sand, samples were prepared with biomass fractions of 20%, 40%, 60% and 80% of the total volume of the mixture.

The mixtures were made so as to maintain the relationship between the initial height of the bed and its inner diameter at a value close to the unit. This measure is in line with what was done by Genehr (2015) and Tannous and Lourenço (2015), in order to minimize the probability of cluster formation in the bed.

Therefore, the total volume of the samples in all tests was approximately the same. Knowing this volume and the bulk densities of the materials involved, as well as the desired biomass volume fractions in each mixture, one can determine the corresponding masses to prepare the samples. The values used are shown in the Table 1 to Table 3, where x_b stands for the biomass mass fraction in the mixtures and x_c for the coal mass fraction.

Table 1 - Composition of the sugarcane bagasse and coal mixture

Biomass volume fraction [%] and code	Mass [g]		x_b [%]
	Coal	Sugarcane bagasse	
20 - 20B	374.39	22.80	5.74
40 - 40B	280.79	45.60	13.97
60 - 60B	187.20	68.40	26.76
80 - 80B	93.60	91.20	49.35

Table 2 - Composition of the sugarcane straw and coal mixture

Biomass volume fraction [%] and code	Mass [g]		x_b [%]
	Coal	Sugarcane straw	
20 - 20S	374.39	12.84	3.32
40 - 40S	280.79	25.68	8.38
60 - 60S	187.20	38.51	17.06
80 - 80S	93.60	51.35	35.43

Table 3 - Composition of the coal and sand mixture

Coal volume fraction [%] and code	Mass [g]		x_c [%]
	Coal	Sand	
20 - 20C	93.60	782.49	10.68
40 - 40C	187.20	586.87	24.18
60 - 60C	280.79	391.25	41.78
80 - 80C	374.39	195.62	65.68

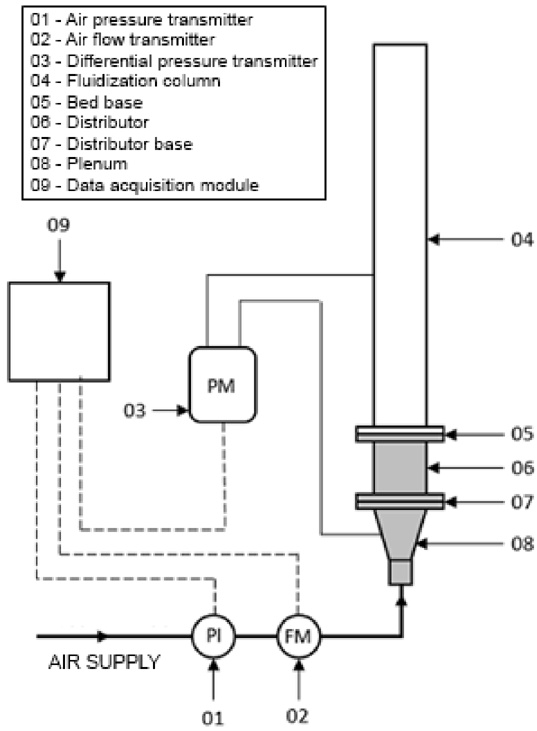
2.2 FLUIDIZATION WORKBENCH

Fluidization tests were performed on a workbench initially designed and built by Genehr (2015), detailed in Figure 2. The fluidization column was made from a cylindrical acrylic tube with internal diameter of 94 mm and wall of 3 mm thickness. The air feed is provided by dry compressed air. The variables measured in this workbench were the air flow rate and the pressure drop along the bed.

Measurement of the injected compressed air flow rate in the bed was performed using an instrument model IFM SD6050. The equipment has a measurement range of 0.2 to 75 Nm³/h, with an accuracy of ± 1.5% and an analog signal output of 4 to 20 mA.

The differential pressure measurement is used to determine the pressure drop across the bed. The pressure ports were made at the bottom of the bed and after the column of material to be fluidized. The differential pressure was measured with a NOVUS instrument, model HUBA 699, with measuring range from 0 to 25 hPa and analogue output of 4 to 20 mA.

Figure 2 - Fluidization workbench scheme



Source: Genehr (2015)

The acquisition and recording of the experimental data were performed by a NOVUS Fieldlogger module. This device has eight analog or digital inputs and supports USB connection for transferring data to a computer. The measuring instruments are connected to the module through cables and fed by a stabilized source, with output voltage of 24 Vdc. All data are recorded at the same time, with acquisition frequency of 1 Hz.

2.3 FLUIDIZATION PROCEDURES

For the determination of the pressure drop curves as a function of the air velocity, the samples were placed in the fluidization column and subjected to the maximum available air flow, of about 50 Nm³/h, for mixing and homogenization of the bed. This procedure prevents initial segregation in the bed during the tests.

Each fluidization test begins with the slow opening of the air supply valve. With the bench in its maximum air flow, the defluidization of the bed begins, with gradual reduction of the air flow, until its complete interruption is reached.

Through all the tests the bed behavior, the fluidization regime changes and the respective air flow rates were observed and recorded. The procedure of mixing, gradual increase of flow and subsequent gradual reduction of flow was done in triplicate for each mixture evaluated.

2.4 DETERMINATION OF FLUIDIZATION CHARACTERISTIC VELOCITIES

By obtaining the pressure drop curves as a function of the air velocity, it is possible to determine the characteristic fluidization velocities for each mixture. Figure 3 illustrates the three pressure drop curves as a function of the air velocity obtained for the 20C mixture. The determined velocities are as follows:

a) initial fluidization velocity - U_{if}: corresponds to the beginning of bed movement. In the mixtures of biomasses and coal, this initial movement is predominantly given by minor coal particles;

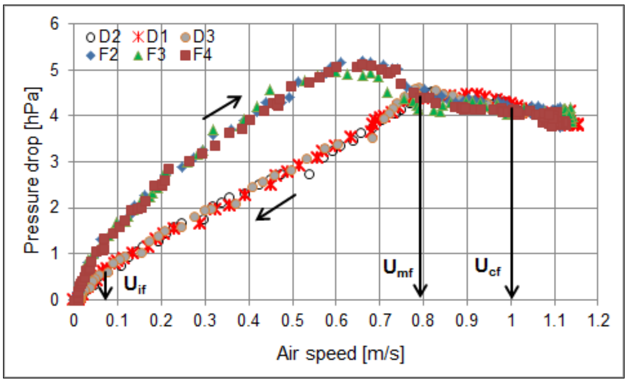
b) minimum fluidization velocity - U_{mf}: according to Wen and Yu (1966) and Tannous and Lourenço (2015), can be determined by the intersection between a line along the fixed bed region and the constant pressure drop line after fluidization;

c) apparent fluidization velocity - U_{af}: defined as the minimum fluidization velocity of the mixture, and graphically identified by the intersection between fixed and fluidized states, as indicated by the U_{mf} for homogeneous particles, as shown in Figure 3;

d) segregation velocity - U_s: Corresponds to the formation of a fully defluidized zone in the upper or lower layer of the bed. It does not occur for all mixtures;

e) complete fluidization velocity of the mixture - U_{cf}: defined as the one at which the pressure drop is quite constant, corresponding to the complete suspension of the particles in the bed.

Figure 3 - Pressure drop vs. air speed curves for 20S mixture



2.4 EMPIRICAL CORRELATIONS

According to Tannous and Lourenço (2015) and Paudel and Feng (2013), several authors have tried to establish empirical models for variables of interest in fluidization processes, such as the minimum fluidization velocity (U_{mf}) for homogeneous particles or apparent fluidization velocity (U_{af}) for binary solids mixtures. According to Paudel and Feng (2013), a good part of these published studies used homogeneous particle correlations adapted for binary particles, using calculated properties such as effective diameter, sphericity, effective mass density and bed porosity.

Some authors have proposed more suitable correlations for mixtures, derived according to the properties and mass fraction of the components and characteristics of the bed (CHIBA et al., 1979; Mourad et al., 1984, see TANNOUS and LOURENÇO, 2015). In general, these correlations use dimensionless numbers, such as Reynolds and Archimedes.

In the case of mixtures containing biomass, generally the existing correlations have limited application to the conditions and plant species used by the authors. According to Tannous and Lourenço (2015) and Paudel and Feng (2013), this is mainly due to the dispersion of available experimental data, caused by the diversity of existing experimental conditions, such as different biomass species, different mass fractions and diameter ratios in mixtures and granulometry, for example.

The minimum fluidization velocity for inert particles can be determined by the drag force method, using the relationship between the Reynolds number and the Archimedes number, given by Eq. 01.

$$Ar = \frac{1.75}{\phi_s \varepsilon_{mf}^3} \mathrm{Re}_{mf}^2 + \frac{150\ (1-\varepsilon_{mf})}{\phi_s^2 \varepsilon_{mf}^3} (\mathrm{Re}_{mf})$$ [Eq. 01]

$$\mathrm{Re}_{mf} = \frac{d_p U_{mf} \rho_g}{\mu_g}$$ [Eq. 02]

$$Ar = \frac{d_p^3 \rho_g (\rho_p - \rho_g) g}{\mu_g^2}$$ [Eq. 03]

$$\varepsilon = 1 - \frac{\rho_{ap}}{\rho_p}$$ [Eq. 04]

In Eq. 01, Ar represents the number of Archimedes, given by Eq. 03, ϕ_s represents the sphericity of the particles, given by the ratio between the surface area of the equivalent sphere and the surface area of the particle, Re_{mf} represents the Reynolds number at the minimum fluidization velocity, given by Eq. 02 and ε_{mf} represents the porosity of the bed in the condition of minimum fluidization, given by Eq. 04.

In Eq. 02, d_p represents the mean particle diameter, U_{mf} represents the minimum fluidization velocity, ρ_g the mass density of the fluid and μ_g its viscosity. In Eq. 04, ρ_{ap} represents the bulk density of the particles and ρ_p their mass density.

Eq. 01 requires the determination of sphericity and porosity of the bed in the condition of minimum fluidization. Wen and Yu (1966) proposed a simplified form for this equation, which avoids the use of sphericity and porosity of the bed. Instead, two constants, K_1 and K_2, are used and are adjusted as a function of experimental fluidization data.

According to Kunii and Levenspiel (1991), K_1 and K_2 remain approximately constant for different types of particles in a wide Reynolds number range. Thus, considering the proposed equations, the Reynolds number can be rewritten as Eq. 05.

$$\mathrm{Re} = (K_1^2 + K_2 Ar)^{\frac{1}{2}} - K_1$$ [Eq. 05]

When one studies the fluidization of mixtures, it is important to use physical properties that describe the whole set of particles present in the bed. Thus, the values of the effective specific mass of the mixture, given by Eq. 06, and the mean effective particle size of the mixture, given by Eq. 07, will be used.

$$\frac{1}{\rho_m} = \frac{x_1}{\rho_1} + \frac{x_2}{\rho_2}$$ [Eq. 06]

$$d_m = d_1 d_2 \left(\frac{x_1 \rho_2 + x_2 \rho_1}{x_1 \rho_2 d_2 + x_2 \rho_1 d_1} \right)$$ [Eq. 07]

$$Ar_m = \frac{d_m^3 \rho_g (\rho_m - \rho_g) g}{\mu_g^2}$$ [Eq. 08]

In both Eq. 06 and Eq. 07, x_1 and x_2 represent the mass fractions of each component of the mixture, and ρ_1 and ρ_2 their respective mass densities. In Eq. 07, d_2 and d_1 represent the mean particle sizes of each component of the mixture.

With this calculation of effective average properties, the mixture is treated as a new single component, and the number of Archimedes of the mixture will be calculated as a function of the effective particle size and the effective mass density of the mixture, according to Eq. 08.

As the mass fraction of biomass (x_b) in the mixture is a parameter of great influence on the fluidization behavior, Paudel and Feng (2013) proposed an equation that takes into account this information, maintaining the same structure and concept of Eq. 05. The result is expressed as the Eq. 09. The authors concluded that Eq. 09 adjusted well enough to their experimental data, with maximum errors in the range of 10%.

$$\mathrm{Re}_{mf} = \left\{30.28^2 + \left[0.046\ (1-x_b) + 0.108 x_b\right] Ar_m\right\}^{0.5} - 30.28$$ [Eq. 09]

3 RESULTS AND DISCUSSION

3.1 CHARACTERIZATION OF MATERIALS

All materials analyzed were characterized in terms of particle shape, mean particle size, mass and bulk density, bed voidage and heating value. The results are presented in Table 4.

Table 4 - Particle properties

Properties	Coal	Sugarcane bagasse	Sugarcane straw	Sand
Shape	Round	Angular	Angular	Round
Mean particle size [µm]	814.9	840.6	931.4	363.0
Mass density [kg/cm³]	1626.9	1164.6	1001.8	2587.0
Bulk density [kg/m³]	717.4	174.8	98.4	1499.4
Bed voidage [%]	55.9	85.0	90.2	42.0
Heating value [MJ/kg]	19.0	17.1	17.4	-

Table 4 shows that the heating values for the three analyzed materials were very close. However, the bulk densities are very different. This impact on the mass of material contained in a given volume, and consequently on the energy that this material can provide. The bulk density of straw is near the half of the one for bagasse, and more than 7 times smaller than the value for coal. Thus, the higher the biomass fraction in the mixture, the lower the energy available in a fixed volume, such as a fluidization bed.

Table 5 - Ultimate composition of the biomasses

Composition	Sugarcane bagasse	Sugarcane straw
Carbon [%]	46.4	43.9
Hydrogen [%]	6.3	6.3
Nitrogen [%]	0	0.6
Sulfur [%]	0.1	0
Oxygen [%]	46.8	48.3

Biomass samples were also characterized for their proximate and ultimate elemental compositions. The results are presented in Table 5 for the ultimate composition and in Table 6 for proximate composition.

Table 6 - Proximate composition of the biomasses

Composition	Sugarcane bagasse	Sugarcane straw
Umidity [%]	8.58	12.19
Ashes [%]	3.56	3.86
Volatiles [%]	74.82	68.90
Fixed carbon [%]	13.05	15.05

Both Table 5 and Table 6 show that the compositions of bagasse and straw are very similar. Table 5 also shows that the sulfur content in these biomasses is close to zero, which is very positive in the context of the energy use of these materials and in the reduction of emissions in thermal energy generation. Table 6 also denotes the low ash content of biomasses, which implies a lower cost with filters and particulate precipitators in the application of these biomasses in the energy industry.

Figure 4 - TGA and FTG results for sugarcane straw

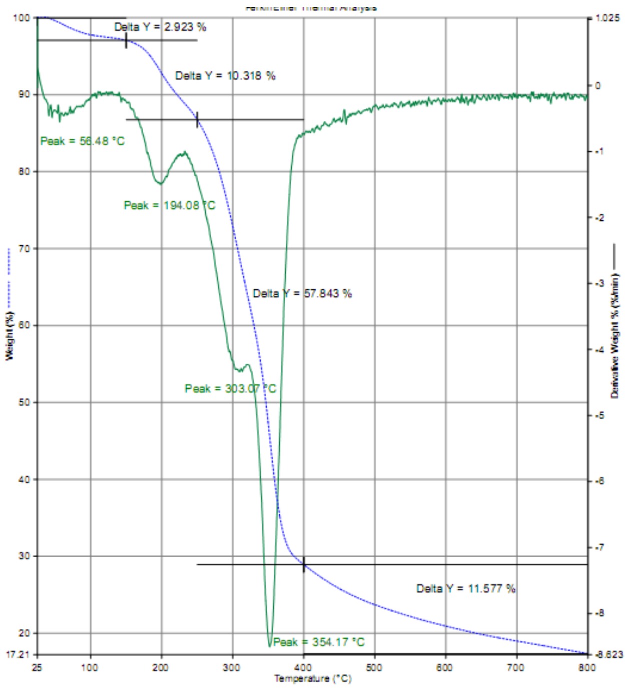


Figure 4 shows the TGA and DTG behavior for sugarcane straw. Both straw and bagasse presented very similar results in this analysis. This is expected, since, as shown in Table 5 and Table 6, the ultimate and proximate compositions are very close for these materials.

The TGA and DTG curves presented in Figure 4 shows that the first occurrence takes place at temperature below 150 °C, and is related to the loss of moisture of the material. The second occurrence is related to the decomposition of the organic matter present in the biomass, whose degradation occurs approximately between 150 and 500 °C, which includes the thermal degradation of hemicellulose, cellulose and lignin. The DTG curve has a peak at approximately 350 °C, which is related to the thermal degradation of hemicellulose and cellulose.

3.2 EXPERIMENTAL CHARACTERISTIC VELOCITIES

The characteristic velocities were determined for the coal and straw, coal and bagasse and coal and sand mixtures. For this determination, only the defluidization curves were considered, due to the better homogeneity of the bed in this condition. The results are presented in Table 7.

Table 7 - Characteristic velocities for defluidization

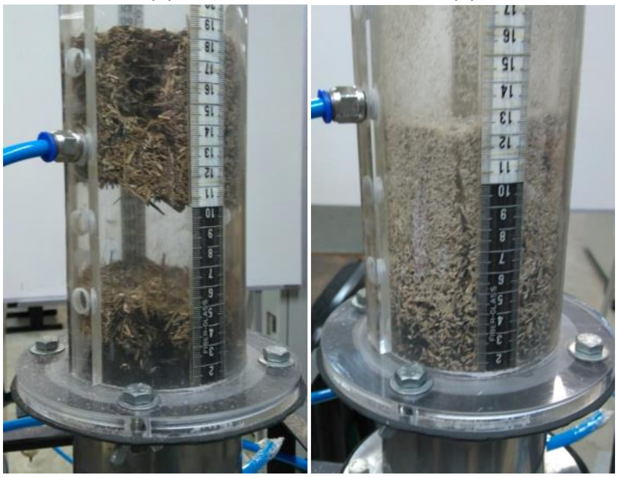
Mixture	U_{if} [m/s]	U_{mf} [m/s]	U_{cf} [m/s]
20B	0.06	0.70	1.00
40B	0.06	0.82	1.10
60B	0.06	0.88	1.10
80B	0.08	1.10	1.20
20S	0.06	0.78	1.00
40S	0.06	0.92	1.10
60S	0.06	1.02	1.20
80S	0.06	-	-
20C	0.03	0.16	0.30
40C	0.04	0.18	0.40
60C	0.04	0.22	0.50
80C	0.06	0.34	0.60
Sand	0.02	0.14	0.30
Coal	0.06	0.58	1.00

Typically, pressure drop in the defluidization regime is smaller than in the fluidization. This characteristic is due to the fact that the bed is already expanded in the defluidization. This difference in the bed behavior is depicted in the Figure 3.

Table 7 also denotes that the 80S mixture was impossible to fluidize, due to formation of preferential paths and clusters in the bed (Figure 5a). The preferential paths also occurred for the 80B mixture (Figure 5b), but the fluidization was still possible, probably because of the smaller mean particle size of bagasse, and its typically less angular particles than straw. Figure 5a shows the formation of a cluster with the size of the bed, completely stopping the fluidization of the mixture. This occurred repeatedly for the 80S mixture. Figure 5b shows some segregation and accumulation of biomass at the top of the bed, and denotes that the preferential paths remain even after the airflow was ceased.

Figure 5 - Fluidization of 80S (a) and 80B (b) mixtures

(a) (b)



3.3 PREDICTION OF CHARACTERISTIC VELOCITIES

The prediction of characteristic velocities was performed in two stages: a) evaluation of the results of the proposed equations for pure inert particles and mixtures between them; b) evaluation of the results of the proposed equations for mixtures of biomass and inert.

Figure 6 shows the comparison between the experimental data and the results obtained from the Eq. 09. All results presented a range of error of less than 15%. The speeds predicted by Eq. 09 were always smaller than the experimental speeds. The worst result was the one for coal. This is probably due to the fact that coal was considered an inert, although the shape of its particles is much more irregular than sand, for example.

The results of Eq. 09 for pure sand and for the mixtures between coal and sand were very near to the experimental values, with errors of less than 10%. This is in line with the results found by Paudel and Feng (2013).

Figure 6 - Comparison of U_{mf} results for inert particles

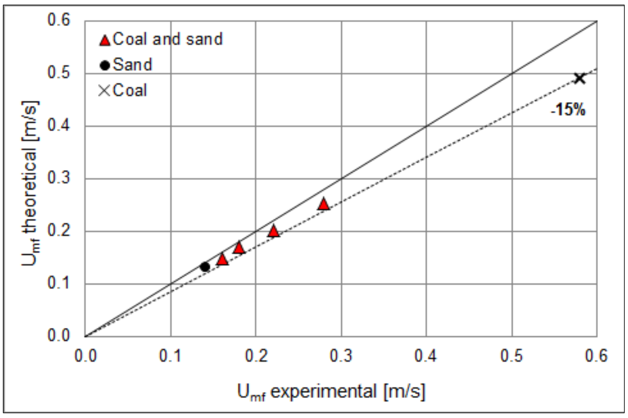
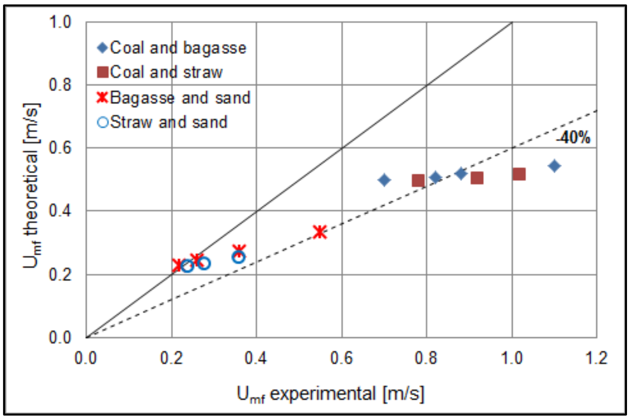


Figure 6 also shows that the mixtures between coal and sand allowed adequate fluidization at lower speeds than that required for pure coal. This aspect is very important from the operational standpoint of a fluidized bed, because higher air velocities imply a shorter residence time of the particles in a combustion chamber, for example, or greater possibility of dragging of the smaller particles.

Figure 7 - Comparison of U_{mf} results for biomass and inert mixtures



The results obtained by Eq. 09 for the inert and biomass mixtures, however, were not as good as those obtained for coal and sand. Figure 7 presents the results from Eq. 09 for mixtures of coal and bagasse and coal and straw. The results of mixtures of bagasse and sand and straw and sand are also demonstrated, for the sake of comparison.

Figure 7 reveals that Eq. 09 was unable to predict the U_{mf} for mixtures with high biomass content. Figure 6 shows that there is already an error of about 15% in Eq. 09 results due to the fact that coal particles were considered as inert from the fluid dynamics standpoint. The results for the sand and biomasses mixtures showed that, even when true inert particles are used, Eq. 09 still fails to predict U_{mf} for mixtures with more than 40% of biomass volume content. The relative errors found in the Eq. 09 results are presented in Table 8.

Table 8 - Theoretical values for U_{mf} and its relative errors

Mixture	U_{mf} theoretical [m/s]	Relative error [%]
20B	0.499	28.8%
40B	0.508	38.1%
60B	0.521	40.8%
80B	0.542	50.7%
20S	0.496	36.4%
40S	0.503	45.4%
60S	0.513	49.7%
20C	0.148	7.3%
40C	0.170	5.4%
60C	0.202	8.0%
80C	0.253	9.8%
Sand	0.133	5.3%
Coal	0.492	15.2%

4 CONCLUSIONS

The characterization of the tested materials showed that the heating values for sugarcane bagasse and straw and coal were very close. Their bulk densities, however, are very different, which has much influence on the fluid dynamics behavior of these particles.

Both the ultimate and proximate compositions of bagasse and straw are similar. It was also verified that the sulfur content in these biomasses is close to zero, what is very important to promote the reduction of emissions in thermal energy generation, through its cofiring with coal, for instance. The ash content is also very low for both biomasses.

The fluidization tests showed that mixtures with high biomass content are very difficult to fluidize, due to severe formation of preferential paths and clusters in the bed. These phenomena occurred for both the sugarcane bagasse and straw. The tests also showed that the mixtures between coal and sand allowed adequate fluidization at lower speeds than that required for pure coal.

The theoretical minimum fluidization velocities for pure sand and for the mixtures between coal and sand were very close to the experimental values, with errors of less than 10%. However, the correlation used was unable to predict the U_{mf} for mixtures with high biomass content. Even when true inert particles are used, the equation still fails to predict U_{mf} for mixtures with more than 40% of biomass volume content.

It was also verified that even the experimental velocities present some degree of uncertainty. The determination of the characteristic velocities by graphical analysis is subject to the intrinsic errors of measuring air velocity and pressure drop in the bed. Moreover, the graphic process is not an exact science.

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