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Elutriation and Sedimentation Process for the Characterization of Sugarcane Bagasse and Straw

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In gas-solid interaction, particle characteristics such as shape, size and density, interacting simultaneously, have a strong influence on the terminal velocity. The behaviour of fluid-dynamics systems acquires great uncertainty when the bed is composed by irregular particles, such as biomasses. Biomass, usually with a wide particle size distribution, is characterized by analyses that do not consider the irregular shape of the particles. Thus, these parameters are introduced in the different theoretical correlations, empirical or combinations of both to represent the biomass behaviour. However, the results obtained in the modelling are generally not satisfactory, because they provide results with considerable deviations. This work aims to compare the drag velocity measured experimentally in biomass (bagasse and straw) with the estimates found through correlations for the determination of the terminal velocity of spherical and non-spherical particles and sieving opening. It was developed appropriated and flexible system to this separation, the superficial air velocity can be regulated to the expected conditions. The material was separated at different air velocities and analysed by known methods for material characterization. The use of elutriation and sedimentation could contribute to the understanding the granulometric and morphological separation of biomass, obtaining separate fractions with homogeneity of size and shape in each fraction obtained, which are not satisfactorily predicted by the correlations used for the design of the fluidized systems for energy generation from biomasses.

1. Introduction

The aim to optimize the process of combustion, pyrolysis and gasification of biomass for energy generation, reduce its impact on the environment and make these more attractive economically, requires a better understanding of the influence of shape, size and density on fluid dynamics processes (Kunni, Levenspiel, 1991; Yang, 2003; Nikky et al. 2014). Given the diversity of biomass, it is difficult to characterize them in a general way through correlations or mathematical models. However, different configurations of fluidized bed reactors are being used in several processes, the biomass particles are mixtures and used in different proportions to obtain their greatest potential.

In the 1970s, the world faced an economic and geopolitical crisis that gave a first hit to the growing, and even unconscionable, energy consumption, therefore one of its main resources, fossil fuels. In the faced with the possibility of the oil depletion, increase in the price of a barrel of oil and the need to use clean and renewable energy, some dependent countries on the importation of this fuel sought energy alternatives. In Brazil, a boost was given to the path of energy generation using sugarcane with the creation of the National Alcohol Program (PROALCOOL), 1975, which received a certain reception by the increase of distilleries and the commercialization of cars fuelled by ethanol (Coelho-Carvalho et al, 2013). Thus, bagasse and straw left over from the sugarcane mill were considered as waste and, like any residue, it was necessary to discard them. The burning of these "residues" for the generation of steam to produce electricity was an alternative that appeared to give a solution to the problem of waste treatment and the creation of new energy resources.

Currently, only bagasse is used as fuel in boilers to produce steam for process and electricity generation. Some mills add sugarcane straw to bagasse, no more than 15 % in weight, but reliable data about this is not available. Until a few years ago, the leaves of sugarcane were burned directly on the plant, before the harvest, in order to facilitate manual harvest. Due to the environment impact that the pre-burning caused, this practice was banned and is being replacing by mechanized harvesting. Sugarcane straw (green and dry leaves and tops) is left on the field after mechanized harvesting. The collecting methods for sugarcane straw still are being studied and developed, but sugarcane straw is already available through mechanized harvesting and the energy contained in this by-product is roughly of some order of magnitude as the bagasse and the ethanol produced (Carvalho, Veiga and Bizzo, 2017)

Bagasse and straw by-product of sugarcane also have great potential as a raw material for the production of fuels derived from processes such as gasification, pyrolysis or hydrolysis followed by fermentation. For the development of these technologies, detailed knowledge of the physical and chemical characteristics of sugarcane bagasse and straw is necessary (Barbosa-Cortez, Silva-Lora, Olivares-Gomez, 2008; Rendeiro et al, 2008).

The use of software in measuring the particles physical characteristics usually requires advanced language programing such as Visual C,Visual Basicand Matlab with specialized image processing toolboxes (Igathinathane *et al*, 2008). The plugins developed for the ImageJ program become a striking option for particle size measurement. ImageJ is a public domain Java processing program, freely available, open source, platform independent and analysis program developed at the National Institutes of Health (NIH) (Bailer, 2006).

The particles entrainment in fluidized bed can be considered as a predictable consequence in fluidized beds (Colakyan, Levenspiel, 1984; Kunni, Levenspiel, 1991), this 'lost material' can be utilized not only to create techniques, also to optimize combustion, gasification and pyrolysis processes (Yang, 2003).

Haider and Levenspiel (1989), from a revision of the existing correlations until that moment to calculate the terminal velocity of the falling particles, u_t, Eq(1), proposed a dimensionless particle diameter, d_*, (Eq(2)) and a dimensionless terminal velocity, u_*, to spherical particles, Eq(3) and non-spherical, Eq(4)

$$u_t = u_* \left(\frac{g\mu(\rho_s - \rho_f)}{\rho_f^2}\right)^{1/3} \quad (1)$$

$$d_* = d_{sph} \left(\frac{g\rho_f(\rho_s - \rho_f)}{\mu^2}\right)^{1/3} \quad (2)$$

$$u_* = \left(\frac{18}{d_*^2} + \frac{0.603}{d_*^{0,5}}\right)^{-1} \quad (3)$$

$$u_* = \left(\frac{18}{{d_*}^2} + \frac{2.3348 - 1.7439\emptyset}{4d_*^{0,5}}\right)^{-1} 0,5 \leq \emptyset \leq 1 \quad (4)$$

Where d_{sph} denote the equivalent spherical diameter, g is the acceleration due to gravity, μ denote the viscosity of fluid, ρ_s and ρ_f are density of particle and density of fluid, respectively; and Ø is particle sphericity.

According to Anderson (1988), Grobart (1973) presented an extensive study on the air entrainment velocity of sugarcane bagasse in various sizes and moisture content (0-48% wb) and developed an equation to calculate the pneumatic entrainment velocity of bagasse, Eq(5).

$$V = 0.115 + 0.819L - 0.0517L^2 + 0.00293LW + 0.00116L^3 \quad (5)$$

Where, V denote the entrainment velocity (m/s), L is the maximum sieve aperture (mm), W denote the moisture content.

Aiming to present an introduction of bagasse dryers connected to the energy recovery system of the boilers operating with exhaust gases, Sosa-Arnao and Nebra (2009) proposed an optimized low cost design for energy recovery configurations to be applied in boilers of water pipes, having as heating fluid the boiler exhaust gas itself. They obtained Eq(6) to determine the terminal velocity of the particle, V_t.

$$V_t = 31.699Dp^{0.324} \quad (6)$$

Where Dp is the mean particle diameter.

Nikky et al. (2014) describes a characterization method of an average drag force between gas and different regular and irregular particles, they performed an experimental investigation with a fluidization characterization test device and presented that the shape and size of the particles have an important effect on the fluidization behavior of the particles by the drag force.

The aim of this work is to aerodynamically characterize the sugarcane bagasse and straw obtained from a sugar mill and compare it with the traditional method of characterization, sieving, to determine the drag velocity.

2. Experimental study

The collection of bagasse and straw was carried out from sugarcane mill, located in São Paulo State. The material was dried in the sun for one week to equilibrate moisture to the environment, samples were taken for the experiments. For the measurement of each measured quantity (including separation) three tests were made, the value presented is the average value. The characterization of the basic properties (density, humidity, equivalent spherical diameter and sphericity) of the previous biomass was carried out in order to estimate the terminal velocity of the particles. The separation experiments by elutriation were executed in the SESY -sedimentation elutriator separator system, illustrated in Figure 1. SESY is composed of a tube riser (R) with a glass section for visual inspection of the fluid dynamic behavior, internal diameter of 0.1 *m* and 1.8 *m* in height. The riser is followed by a U-bend downward to end in a sedimentation chamber (SC). Air suction is performed by an air exhaustor (AE). A filter is placed between the sedimentation chamber and the air connection to avoid the output of the material. Air velocity was controlled by valve (V). The material to be separated by elutriation is spread in the vibrating feeder system (VS) to dose the biomass into the riser. The dragged material is collected in the sedimentation chamber and the sedimented material is collected at the bottom of the riser to be feed in the vibrating system at the next speed. The air flow rate was measured with an orifice plate system (OP) constructed in accordance with ASME MFC-14M/2003 standard and pressure was measured with Smar LD301 transducers (P). The air temperature of the system was measured to determine the air density. The device is able of producing superficial air velocities between 0.5 and 6.5 *m/s*.

Using atmospheric air at ambient pressure and temperature as the working fluid, an airflow was generated in the riser at different velocities, where biomass particles were feed in the airflow. The feeding of the particles was done continuously and in small quantities, preventing a large amount from being simultaneously arranged in the riser, in order to minimize the agglomeration of particles.

The density of biomass samples was measured with water pycnometry. The Sauter diameter was calculated based on weight fraction of the separated material by sieving. The projected area of the particles was obtained by image scanning. The ImageJ program was used to measure this dimensions, as well as major and minor axis length for the calculation of sphericity, Eq(7), based on Wadell's original definition. These dimensions are described by Baxes (1994).

$$\emptyset = \left(\frac{d_v}{d_s}\right)^2 \quad (7)$$

Where d_v is the surface area of a sphere of the same volume as the particle, and d_s is the actual surface area of the particle.

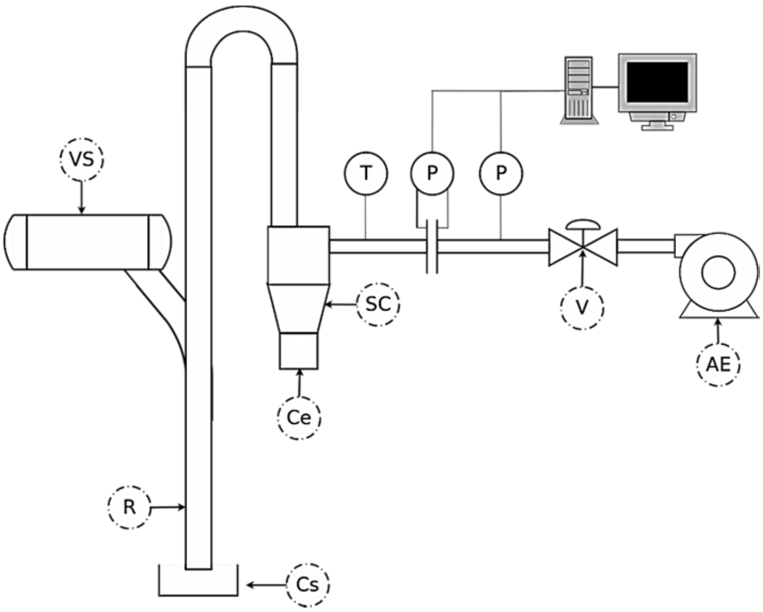

Figure 1: Experimental bench SESY. Air exhaustor (AE), elutriated material collector (Ce), sedimentary material collector (Cs), pressure gauge (P), riser (R), sedimentation chamber (SC), temperature gauge (T), valve (V) and vibratory feed system (VS).

The bagasse was separated with velocities of 0.65 to 6.53 *m/s* and straw at 0.65 to 5.50 *m/s*. For the terminal velocities predicted by correlations the size distribution obtained by sieving was used. Three correlations were used: the equation presented by Grobart (1973) and the correlations of Haider and Levenspiel (1989) for spherical and non-spherical particles.

3. Results and analysis

Figure 2 shows the results of the preliminary sieving for bagasse and straw. From Figure 2, it can be seen that the biomass is concentrated in the larger sieves (51% for bagasse and 32% for straw). The biomass properties are presented in Table 1.

Table 1: Biomass sample properties.

Biomass	Density (kg/m^3)	Sauter mean diameter (μm)	Φ	W (%)
Bagasse	617 ± 174	684 ± 50	0.67	5 %
Straw	333 ± 82	1036 ± 118	0.76	3 %

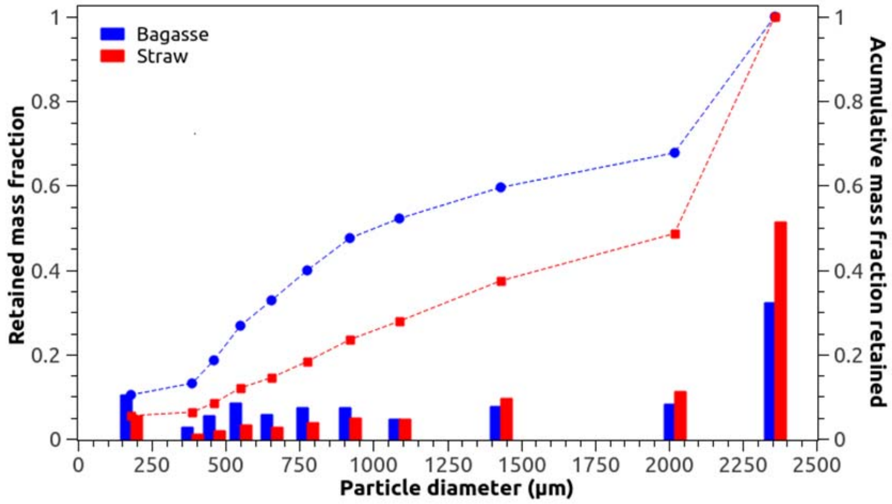

Figure 2: Sieving analysis on particle size distribution.

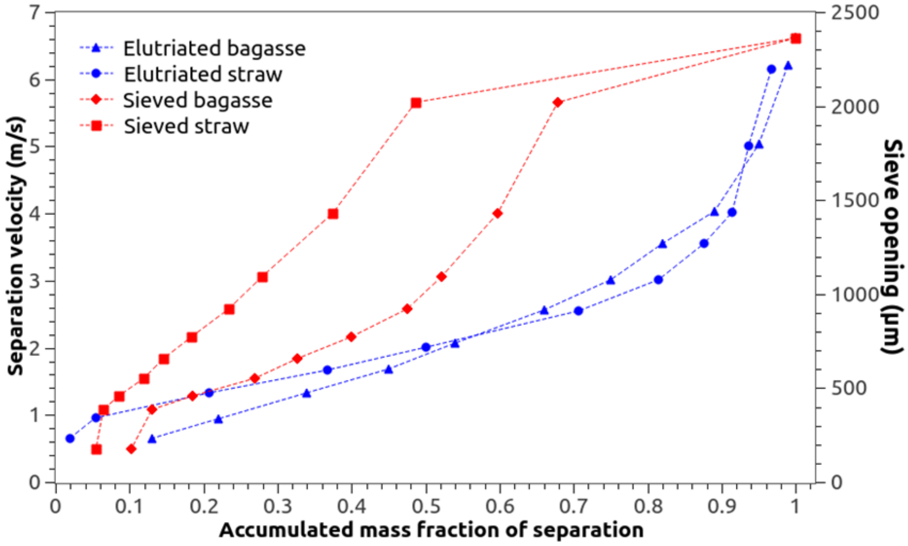

Figure 3: Sieving analysis on particle size distribution

Due to velocity limitations of the measuring system, it was able to separate by elutriation 98% of the bagasse and 97% of the straw. Figure 3 shows the accumulated mass distribution for both bagasse and straw for separation, by elutriation and sieving. Clearly, Figure 3 presents that due to the higher concentration of bagasse particles in the sieves with higher mesh opening, it need higher velocity than the straw to be dragged. From Figure 3, we notice that the behavior of particles separated by elutriation and the particles separated by sieving is very different, showing the influence of the irregular shape and size of particles.

Figures 4 and 5 show the accumulated mass fraction as a function of the terminal velocity of the particle both measured in the elutriator and predicted by correlations for the bagasse and the straw, respectively. In the case of bagasse, Figure 4, a good agreement was found between the measured elutriation velocity and the one obtained by the Haider and Levenspiel (1989) equation for non-spherical particles up to 2.52 *m/s*. For straw, a slight approximation was found between the measured elutriation velocity and the one obtained by Haider and Levenspiel (1989) equation for non-spherical particles ut to 2.00 *m/s*. It should be noted that the velocities provided by the correlations are lower than those measured experimentally, e.g., for the estimation of the terminal velocity of the coarse fraction of bagasse, sieved with higher mesh opening and calculated with the equation Haider and Levenspiel (1989) for non-spherical particles, is 55 % (59 % for straw) less than the measured value for the coarse particles of bagasse separated by elutriation at the highest velocity.

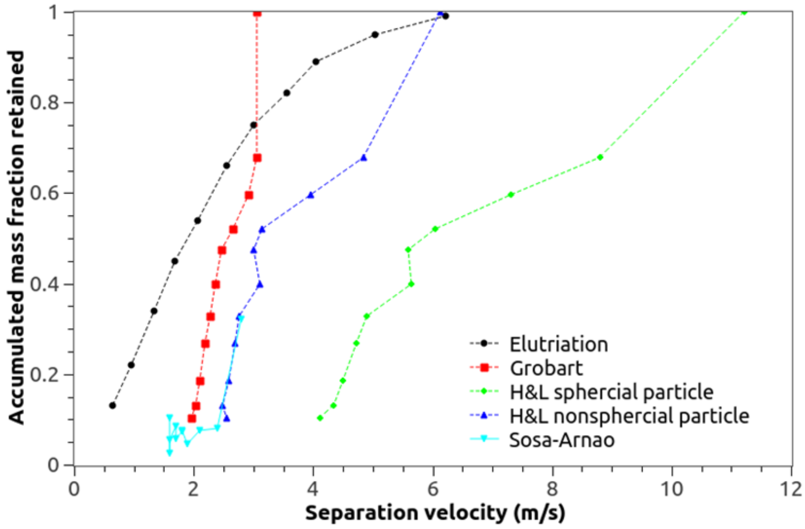

Figure 4: Mass fraction accumulated versus terminal velocity of bagasse particles, measured and predicted by correlations of Grotart (1973), Haider and Levenspiel (1989), and Sosa-Arnao and Nebra (2009).

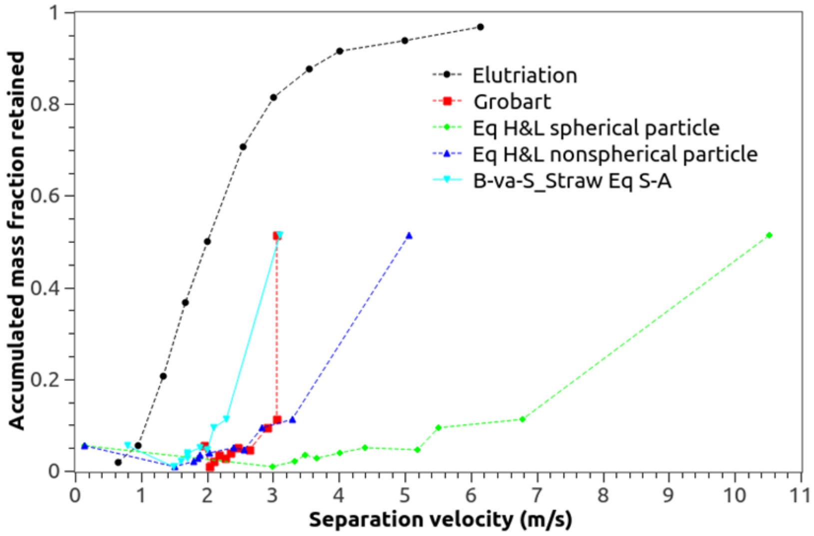

Figure 5: Mass fraction accumulated versus terminal velocity of straw particles, measured and predicted by correlations of Grotart (1973), Haider and Levenspiel (1989), and Sosa-Arnao and Nebra (2009).

4. Conclusions

The results showed great difference between separation techniques by sieving and elutriation for characterization of size particles. Terminal velocity values obtained experimentally differ, in large part, of the value calculated by classical correlations of literature, due to the variety and irregularity of the particle shape and size distribution from biomass.

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