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Physical characterization of sweet sorghum bagasse, tobacco residue, soy hull and fiber sorghum bagasse particles: Density, particle size and shape distributions

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ABSTRACT

Biomass offers an alternative to meet the increasing interest in renewable energy. For thermal conversion processes such as fast pyrolysis, which often involve fluidization, spherical particles are considered unsuitable for materials such as biomass. An investigation was made of relevant physical properties of four types of biomass: sweet sorghum bagasse, tobacco waste, soybean hulls and fiber sorghum bagasse. Three samples of each biomass with different granulometries were analyzed. Density values were determined. Particle shape and size distributions were evaluated by digital image analysis. It was observed that the moisture content affected the materials' true density and for dried biomass the smaller the particle sizes the higher the true density. The results indicated that sweet sorghum bagasse particles of different sizes have similar shapes; that the particle roundness of the four types of biomass is a property more closely related with the characteristic shape of the material than with its granulometric classification; and that the granulometric classification of tobacco waste, soybean hull and fiber sorghum bagasse particles can effectively influence the obtainment of particles with higher or lower roundness. The average roundness varied from 0.45 to 0.70 and the aspect ratio from 1.90 to 2.60. The results obtained in this study are useful for numerical simulations of the fluid dynamics of pyrolysis, combustion and gasification processes and also for studies about the optimal operating conditions of mixture fluidization.

1. Introduction

Interest in renewable energy grows steadily as fossil fuels are consumed and the environmental problems they cause have intensified [1]. Biomass is an alternative energy source for generating fuels and value-added compounds [2]. Thermal conversion processes are options to convert biomass into the aforementioned products [1,3].

Some of the industrial and agricultural wastes available in Brazil are sweet sorghum bagasse, tobacco waste, soybean hulls and fiber sorghum bagasse.

Sweet sorghum cane complements the production of sugar cane [4]. The cultivation of sweet sorghum for ethanol production is on the rise and experts affirm that sorghum will extend the ethanol production season by 60 days or more [5]. Sorghum cane, which can be processed in the same facilities as those designed for ethanol production from sugar cane, generates large amounts of fibrous waste (bagasse) [6]. It is estimated that the cultivated area in Brazil has expanded from 3000 ha in the 2010/11 crop to 20,000 ha in the current crop [7].

Tobacco leaves are the raw material for cigarette and cigar production, whose industrial process generates tobacco waste [8,9] that represents about 20 wt.% of processed dry tobacco [9]. Part of this waste can be employed in the manufacture of cigarettes (maximum of 15 wt.% of waste) after undergoing an extrusion process. Tobacco waste can also be used as agricultural fertilizer, but its use is limited since this material has a high content of nicotine, which is a toxic compound. Most tobacco waste represents a significant amount of biomass to be treated [10].

Soybean hulls are a by-product of industrial processing for the extraction of soybean oil. Soybean hulls represent 2% (in weight) of the whole grain. This by-product is readily available in the domestic market because of Brazil's extensive soy production. The inclusion of soy hulls in animal feed is economically viable and is the main product in which they are applied [11]. Estimates by Brazil's Ministry of Agriculture, Livestock and Supply (MAPA), albeit as yet unconfirmed, indicate that the country's soybean production is expected to reach 80 million tons (2012/2013 crop).

Several on-going research processes in this country focus on the development of a new variety of sorghum called fiber sorghum. The aim is to produce a modified material with high biomass productivity and high calorific value. The cultivation of this type of sorghum, whose stalks are longer than those of sugar cane, has the potential to render it an alternative source of energy for Brazil. Sorghum bagasse can also be used for the production of second-generation ethanol via enzymatic hydrolysis. This type of sorghum is well suited to the industrial process and has a short life cycle, since it can be planted and harvested in about 120 days.

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Fast pyrolysis is an efficient and promising process of thermal decomposition of organic materials in the total or partial absence of oxygen to produce condensable vapors, volatile non-condensable gases and solids (char). After condensation, the liquid fraction of the pyrolysis process can be converted into fuels and chemical products. To increase the production of condensable vapors, the biomass thermal conversion process must be fast, a condition that is ensured by high biomass heating rates and short residence times of the organic material inside the reactor [12]. The best conditions for fast pyrolysis include temperatures of 400 to 600 °C; residence times of 0.5 to 2.0 s; particles smaller than 5 mm with less than 10% of moisture content [13]. Therefore, biomass is usually dried and ground in preparation for the pyrolysis process.

Experimental studies reported in the literature [14] demonstrate that bubbling fluidized beds have the potential for fast pyrolysis of various types of biomass. The bubbling fluidized bed can produce larger amounts of condensable vapors than other types of equipment, such as, for example, vacuum reactors, ablative reactors and circulating fluidized bed reactors.

The addition of an inert material in the bubbling fluidized bed reactor causes the heat transfer coefficient (inert-biomass) to increase, ensuring favorable conditions for fast pyrolysis. The fluid dynamic behavior of a fluidized bed composed of a binary mixture (biomass and inert) is strongly influenced by the difference in the physical properties of the particles, especially their density and size and shape distributions [15].

Thus, the development of thermal conversion processes requires studying the influence of the shape, size and density of particles in the conversion of biomass. In a fast pyrolysis unit, the biomass to be processed usually has a wide range of sizes and shapes [1]. Different particle shapes and sizes result in different surface areas and volumes, which are characteristics that directly affect the phenomena of heat and mass transfer, and oxidation and volatilization rates [3]. Besides, the irregular shape of biomass particles hamper the appropriate functioning of feeders in gasification, combustion and pyrolysis reactors [16].

Studies have been conducted to investigate how biomass particle shape and size influence the process of pyrolysis and volatilization [1,3,17]. Shen et al. [1] studied the effect of particle size (0.18–5.6 mm) on the yield of wood-derived bio-oil produced in a fluidized bed. These authors reported that larger particles of up to 1.5 mm produced lower bio-oil yields, although they did not observe significant variations in yield with particles larger than 1.5 mm. Lu et al. [3] found that in a fluidized bed reactor, wood particles of quasi-spherical shapes showed lower rates of volatilization and higher yields of char than less spherical particles (cylindrical or disk-shaped particles) with similar masses and under the same reaction conditions. They also observed that larger particle sizes of all the analyzed shapes produced lower yields of volatiles. Reddy and Mahapatra [17] reported that the agglomeration of particles in a circulating fluidized bed leads to more effective pyrolysis when the char generated contains larger quantities of very fine or very coarse particles, or of both in high quantities.

Other studies about variation in particle size and shape of different types of biomass are also being conducted. Driemeier et al. [18] characterized different types of sugarcane bagasse particles, applying different milling conditions to prepare the materials and characterizing their samples using laser diffraction techniques and scanning electron microscopy. They reported differences in size distribution due to the different milling conditions and the presence of fractions of fibrous particles in all the analyzed materials. Guo et al. [19] characterized four types of biomass: pine, bean stalks, rice husks and sugarcane, using image analysis and sieving. They reported that the biomasses showed high aspect ratios, which decreased with diminishing particle size. Moreover, they found similar size distributions in the different types of biomass under study.

Approximating or simplifying particles as spherical is unsuitable for irregular particles such as those of biomass [3]. For samples of non-spherical particles, it is known that the different technologies available, such as sieving and laser diffraction, may lead to very discrepant results [20]. Most studies on lignocellulosic materials describe particles as flake, rod or needle-like, but there are few studies about the real shape of particles [19]. Understanding the physical and chemical phenomena involved in the degradation of biomass inside the reactor is crucial for the development, optimization and scale-up of the pyrolysis process.

The main focus of the present work was to investigate relevant physical properties such as density, size distribution, aspect ratio and roundness of four types of biomass: sweet sorghum, tobacco waste, soybean hulls and fiber sorghum. The physical properties of these biomasses are important in determining the optimal conditions of bubbling fluidization of binary mixtures. The choice of the ratio of biomass to inert material that favors a good mixture and minimizes the segregation of the solid phases in the bed is important for the success of the pyrolysis process. The knowledge about the physical properties of biomass particles is also useful for simulation and modeling studies. All the biomasses investigated here present a potential for application in the fast pyrolysis process.

2. Materials and methods

2.1. Materials

Sweet sorghum bagasse was supplied by Monsanto do Brasil Ltda. The biomass, which was received in the form of dry stalks, had already undergone a process of crushing to extract its broth and pre-drying at 105 °C for 24 h. The as-received sorghum was chopped into smaller pieces and ground in a knife mill, after which the particles were classified by sieving in three size ranges, as indicated in Table 1.

The tobacco waste was obtained from the Uberlândia-MG plant of the company Souza Cruz. For the analytical procedures, the tobacco waste was classified by sieving into three size ranges.

The soybean hulls were donated by the Uberlândia-MG plant of the company Cargill Agricola S/A. The sample was ground in a knife mill, sorted by sieving into three size ranges.

The fiber sorghum stalks were also supplied by Monsanto do Brasil Ltda. The stalks were first subjected to a preliminary operation to reduce their size without crushing (cutting them into about 1-inch long pieces), after which the pieces were placed in a knife mill and the resulting ground bagasse was dried at 105 °C for 24 h. Despite the low moisture content of this material, drying is important to minimize the proliferation of fungi that feed on any residual sugar [21]. Thus, after drying, the sample was ground once more in a knife mill and then separated into three size ranges by sieving.

Table 1 shows the ranges of particle sizes for the four types of biomass analyzed in this study. The samples were classified as described by Geldart and Abrahamsen [22].

Fig. 1 illustrates the materials used in this study. Note the differences in particle size and shape of the biomasses with different granulometries.

Table 1
Size ranges of particles for sweet sorghum bagasse, tobacco residue, soy hulls and fiber sorghum bagasse.

Samples	$d_{\#}$ [μm]	Geldart	Symbols
Sweet sorghum bagasse 1	125–355	B	SB1
Sweet sorghum bagasse 2	355–500	B	SB2
Sweet sorghum bagasse 3	500–850	B	SB3
Tobacco residue 1	125–355	B	TR1
Tobacco residue 2	355–500	B	TR2
Tobacco residue 3	500–850	B	TR3
Soy hulls 1	150–425	B	SH1
Soy hulls 2	425–710	B	SH2
Soy hulls 3	710–850	B	SH3
Fiber sorghum bagasse 1	150–425	B	FS1
Fiber sorghum bagasse 2	425–710	B	FS2
Fiber sorghum bagasse 3	710–850	B	FS3