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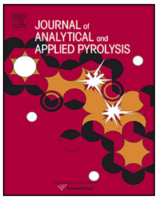

Bio-oil production from Colombian bagasse by fast pyrolysis in a fluidized bed: An experimental study

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ABSTRACT

We present experimental results of fast pyrolysis of sugarcane bagasse in a fluidized-bed reactor, in which temperature, biomass feed rate, carrier gas flow, biomass, and effects of inert material particle size on global product distribution were evaluated. For this, changes in the fluid dynamic parameters were made (fluidizing gas flow between 20 and 60 L/min, biomass feed rate between 2.0 and 5.3 kg/h, and inert material particle size between 0.20 and 0.5125 mm). Experimentally, we found that the highest yield of bio-oil was obtained when the reactor was operated at 500 °C, with a carrier gas flow (nitrogen) of 50 L/min, particle size of the inert material and biomass both between 0.600 and 0.425 mm, and biomass feed rate of 2 kg/h. Under these conditions, yields of 72.94% (w/w), 23.28% (w/w), and 3.79% (w/w) for bio-oil, biocarbon, and permanent gases were reached, respectively. Our results show synergic effects between reactivity and fluid dynamics on a fluidized bed, which ensures an efficient, fast pyrolysis process. Therefore, there are two competitive effects related to the particle diameter: first, the yield increases due to heating severity; second, the yield decreases due to entrainment of the smallest particles.

1. Introduction

Alternative energy sources, such as solar, wind, and those obtained by thermochemical and biochemical transformations of biomass, must compete with traditional oil and coal-derived resources, satisfying the requirements of availability, price, transportation, and environmental and social impact, among others. In this sense, biomass transformation is emerging as an attractive option for Colombia, where it has great potential to meet the demand for sustainable and green energy. Annually, up to 72 million tons of residual biomass are collected, which represents 331 TJ/year of potentially useful energy [1].

Biomass can be transformed into high-energy fuels by biological or thermochemical processes. Biological processes are more selective and require long reaction times in contrast to the thermal processes, which provide multiple and complex products in short reaction times [2]. Among thermochemical processes, combustion, gasification, torrefaction, and pyrolysis are their main exponents.

In pyrolysis processes, biomass is subjected to heating in an inert atmosphere to produce biochar, bio-oil, and permanent gases, whose yields depend on the operating conditions. Pyrolysis at lower heating rates (5–100 °C/min) and temperatures of 400–600 °C is known as slow pyrolysis and is characterized by a high production of biochar (35–40% (w/w)) and low yields of bio-oil (between 25 and 30% (w/w)) [2–5]. In contrast, fast pyrolysis is characterized by high heating rates (>1000 °C/s), temperatures between 300 and 500 °C, and fast cooling of condensable vapors to produce bio-oil as a main product (60–70% (w/w)), 10–15% (w/w) of biochar, and approximately 15–20% (w/w) of permanent gases [2,5–8].

Bio-oil is a viscous, brown liquid, which has a similar high heating value as biomass, approximately 16–19 MJ/kg [2,5,9]. Its chemical composition is complex and depends on the nature of the physicochemical biomass, reaction conditions, and the technology used in the thermal decomposition [5,9]. There are several technological developments for bio-oil production based on fast pyrolysis: pyrolysis in a fluidized bed, free-fall reactors, rotating cone technology, ablative pyrolysis reactors, hot wire (wire mesh), and screw reactor (auger reactor), among others [2,5,8–10].

Fluidized bed and free-fall reactors are the most common technologies reported in the literature and applied in industry (e.g., Dynamotive, EnSyN, METSO/UPM) due to low construction and operating costs in comparison with other alternatives [5,10–12]. Indeed, in 2002, the University of Waterloo in Canada began a project for the construction of a fluidized-bed pyrolyzer to produce

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bio-oil with a capacity of 100 ton/day. The reactor began operating in February 2005. However, in 2008, the operation had to be stopped because it was not possible to reach the estimated capacity of the original design [13,14].

Furthermore, in 2006, a second plant with a capacity to produce 200 ton/day began operating [14]. The bio-oil produced was used in a 2500-GT turbine to produce electricity. However, due to variations and limited bio-oil quality, turbines were not used again [14]. Similar experiences have been stopped due to many problems associated with design, scale-up, and start-up. Problems for industrial-scale, bio-oil production are based on the lack of knowledge pertaining to the devolatilization process itself; currently, the decomposition of the biomass kinetics is not clear, and interactions between solid, liquid, and gas phases inside particles have not been well understood. However, the development of this technology does not compete with food security, unlike the transesterification and fermentation processes for producing ethanol and biodiesel, respectively. Additionally, bio-oil can be upgraded, stabilized, and easily incorporated into the existing infrastructure for oil refining; this reduces operating costs compared with the gasification of the same residues [3,15,16]. Also, there is a need to evaluate the interactions between cellulose, hemicellulose, and lignin during pyrolysis and how these kind of macromolecules can affect mass, energy, and momentum transfer processes [17,18].

Many parametric studies of biomass pyrolysis on a fluidized-bed reactor have evaluated the temperature, fluid dynamics, and particle size of bio-oil, biochar, and gas yields. Lira et al. [19] evaluated the effect of temperature on bio-oil, biochar, and gas global yields between 400 and 600 °C, holding the biomass particle size (Amazon tucumã <2 mm) and carrier gas flow ($N_2 = 30 \times 10^{-5}\ \mathrm{Nm^3/s}$) constant. The optimum temperature to reach the highest bio-oil content was 550 °C, obtaining a 60% (w/w) of yield, from which 20% (w/w) was water. Similar results at 350 °C were reported by Kim et al. [20] for the *Miscanthus sacchariflorus* pyrolysis; the bio-oil yields reached approximately 57.2% (w/w) with a low water content (approximately 25% (w/w)). Additionally, the researchers illustrated that gas residence time is a critical factor for bio-oil quality because gas residence times higher than 1.9 s bring on secondary reactions of vapors. Within this framework, Wang et al. [21] compared the global yields of four biomasses abundant in China (Manchurian ash, China fir, Padauk wood, and rice straw), which were pyrolyzed on a bed reactor at high heating rates. The highest yields were obtained at 500 °C for China fir, Padouk wood, and rice straw and at 550 °C with Manchurian ash. Their biomass feed rate (between 1.4 and 2.6 kg/h) did not have any effect on the bio-oil yield. The highest bio-oil content, which reached up to 55.7%, was obtained from Padouk wood, and 24.6% (w/w) was water. This biomass has the lowest mineral matter content (0.44% (w/w)). In contrast to the 12.2% (w/w) from rice straw, which had a yield of only 33.7% (w/w) with a 53.5% (w/w) for water. Other researchers [22] pyrolyzed sawdust in a fluidized-bed reactor on a bench scale (internal diameter [ID] = 80 mm, height [H] = 300 mm) and evaluated the temperature, particle size, feed rate, and carrier gas flow effects of the global yields. Furthermore, the highest bio-oil yields (approximately 60% (w/w)) and particle sizes greater than 1.3 mm were achieved at 450 °C; at less than 0.3 mm, there is a negative effect on the global product distribution due to a secondary reaction within the particles and sweep through. When the biomass feed rate was varied from 2.5 to 1.5 g/min, the bio-oil was reduced by only 3%. In addition, Heidari et al. [23] performed fast pyrolysis tests with eucalyptus wood on a fluidized-bed reactor. This study is the most complete one we found in the scientific literature related to parametric evaluation (temperature, carrier gas flow, particle size, and biomass feed rate) about the product distribution. Increasing the carrier gas N_2 between 10 and 15 L/min yields bio-oil between 50% (w/w) and 60% (w/w). Related to particle size, they showed that at 1.5 mm it reached the greatest yields, and this is reduced at 10% for higher sizes, due to volatiles secondary reactions inside the particle. The greatest yields are reached at 450 °C (50% (w/w)); meanwhile, the previous one is reduced to 35% (w/w) when the reactor is operated at 600 °C, being that the noncondensable gases yield nearly 50% (w/w). Related to feed rates, there was a parabolic tendency, in which the maximum bio-oil production was achieved at 90 g/h. The feed rates have a direct relationship over the fluidization pattern, product gases flow, solid mixed, heat transfer, volatiles residence time, and secondary reactions. Choi et al. [24] found similar results for sawdust pyrolysis. This research, contrary to previous ones, took into account the condenser temperature for the recovered bio-oil. The bio-oil increases when the cooling temperature reached 10 °C (56% (w/w)) instead of 40% at 40 °C. Lower temperatures promoted bio-oil and biochar lagging, making the product quantification difficult. Similar work related to parametric studies have been reported [25,26].

Most of studies have been performed on bench-scale reactors, in which the product quenching is higher up to 0 °C. Little research have been conducted with fibrous biomass, such as sugarcane bagasse, due to difficulties with the dosification. The inert material particle size of the composition and global yields of permanent gases have not even been explored. Sugarcane bagasse has a high potential of bio-oil production by thermochemical methods due to its high volatile matter content (nearly 80% (w/w)). In addition, these are the most abundant agro-industrial waste in Colombia, having a potential production of 72 million ton/year of biofuels. Additionally, the particle size effect of the inert material needed to enhance the fluid dynamics and heat transfer behavior have not been described.

In this article, temperature, biomass feed rate, carrier gas flow, biomass, and effects of inert material particle size were evaluated based on the global product distribution and composition of permanent gases. Variations were made in the fluid dynamic parameters (e.g., fluidizing gas flow and particle size of the biomass and inert material) to determine the most appropriated operational condition set.

2. Experimental

2.1. Materials and methods

The raw material used was sugarcane bagasse, which is a by-product from the sugar refinery industry in Colombia. This material is produced from the milling step after passing a set of five or six roller mills. Its moisture content reaches approximately 35% (w/w), and its fiber size is 3–5 cm in length on average. To meet feed characteristics for the pyrolysis process, a solar drying step was performed. Then material was ground with a hammer mill of 5 kW power and 3000 rpm, and sieving was performed until a product with uniform particle size (average: 0.5125 and 0.075 mm) and moisture content below 10% (w/w) was obtained. Once the biomass was prepared, physicochemical characterization was performed (e.g., elemental, proximate analysis and lignocellulosic material content).

2.2. Raw material characterization

Biomass particles with an average size less than 0.25 mm (size 60 mesh) are required for analytical procedures. To establish the biomass elemental composition (CNHOS), an adjustment of the ASTM D5373 standard was used by applying an EXETER CE 490 elemental analyzer. The ultimate analysis was performed by adapting the ASTM protocols established for coal but applying them to biomass. For determination of lignocellulosic material content,