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Steam gasification of biochar derived from elephant grass pyrolysis in a screw reactor

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ABSTRACT

Steam gasification of biochar has emerged as a promising method for generating bioenergy. In this study was investigated the steam gasification of biochar derived from the elephant grass pyrolysis and evaluated regarding the influence of biochar properties on the steam gasification process. Firstly, elephant grass pyrolysis experiments were performed at 400, 500 and 600 °C in a screw reactor in order to obtain biochar. The biochars were characterized according to FTIR, surface area (BET), and alkali and alkaline earth metals. For biochar produced at 500 °C, steam gasification experiments were conducted at 800, 850, 900 and 950 °C in a fixed-bed reactor, while others biochars were subjected the steam gasification at 900 °C. The maximum reaction rate (dX/dt) of the biochar occurred during the reaction's initial time (t < 3 min), while at 950 °C the reaction rate rose again during the interval time 12–15 min. Likewise, the H_2 maximum reaction rate was observed during the interval between 0 and 3 min (≈4.6 mmolH_2/min·gbiochar). Results also show that as gasification temperature (800–950 °C) increased, H_2 yield significantly escalated (52.00–82.02 mmol·gbiochar^{-1}), the same was true for dry gas yield (1.54–2.67 N m^3·kg^{-1}). In addition, the Arrhenius parameters and the reaction model of the steam gasification of biochar derived from elephant grass have been estimated from some kinetics models available in the literature (VM/GM/RPM).

1. Introduction

Non-renewable sources of energy have been responsible for more than 85% of the world's energy requirements. In their study, Sing et al., projected a scenario in which the world's annual energy consumption would increase from the current value of 500 to 1000–1500 Exa Joules per year until 2050 [1]. In recent years, renewable energy has received great attention due to high anthropogenic emissions of greenhouse gases to the atmosphere. Biofuels production from thermochemical conversion of biomass has been widely studied as an alternative to replace non-renewable energy sources.

Biomass is the only resource capable of producing chemical products and electricity among all the renewable alternatives. The use of biomass is increasing rapidly as a result of its versatility in feedstock and its applications. As an example, these applications can cover a wide variety, from direct combustion for heat and power generation to biofuel synthesis in order to obtain chemical products with high economic value [2,3]. However, despite biomass energy's many advantages, commercial scale is not yet fully developed. The biggest challenges are found in supply chain management and conversion technologies [4].

According to Hlavsová et al., among the renewable energy resources such as biomass, energy crops are of particular interest. The projection indicates that by 2050 energy crops will have the potential to deliver about 200–400 Exa Joules/year at a competitive cost. Energy crops are preferred over other types of biomass for energy generation. This is due to their high productivity, low investment costs, low environmental maintenance, short period between planting and harvesting, and high energy values. Among energy crops, perennial grasses such as elephant grass possesses all, these aforementioned characteristics [5].

Elephant grass (*Pennisetum Purpureum Schum*) is a monocot C4 perennial grass of the Poaceae family, which is a promising source of renewable energy due to its fast growth (can be harvested up to four times a year), disease resistance, easy adaptability and can grow on different types of soils. Specifically in Brazil, this biomass production is about 30 tons per hectare and have the potential to produce up to 1.2 Gt of charcoal and 2 Gt of bio-oils per year [6]. In addition, biochar derived from elephant grass pyrolysis has some specific properties that recommend its use in gasification processes. Its high content of

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potassium is also of important mention.

Biomass can be converted by thermochemical and biochemical processes. Biomass conversion enables the production of alternative and versatile fuels/products such as bio-oil, biochar, bioethanol and syngas. In addition, thermochemical processes, such as gasification and pyrolysis, are considered the most promising solutions for biofuels production and energy supply [3].

Gasification is considered to be a key technology for large-scale biomass exploitation. Biomass gasification using steam as gasifying agent can produce a hydrogen-rich gas. Moreover, syngas (H_2 + CO) with appreciable yield can be obtained from the process. Previous investigations have reported that the steam gasification of biochar is 2–3 times faster when compared to coal gasification [7,8]. The steam gasification processes of biochar have several advantages, such as volatile matter (bio-oil and tar) removal during the pyrolysis stage, it also does not require the use of catalysts in the gasification process, making it cheaper. Studies reported that the operating conditions are not complex and the obtained gas contains a high content of H_2 and CO [9–11].

Many types of reactors have been used for biochar production from biomass pyrolysis (fixed-bed/fluidized bed/conical spouted bed). However, few studies on biomass pyrolysis in screw reactors have been reported in the literature. Screw reactors, also known as auger reactor, have major strengths in design compactness and simplicity, little or no carrier gas requirement, easy separation of bio-oil and biochar, and lower energy requirements. The simple operation of the screw reactor is also an advantage regarding farm scale utilization/application [12].

H_2 is considered a clean fuel because its combustion does not release CO_2. In addition H_2 can be easily and directly used in fuel cells, turbines for electricity generation, internal combustion engines as well as transport fuel. Besides these direct applications, H_2 can also be an intermediate fuel to produce gasoline, ethanol, methanol and a myriad of other chemicals products. Nowadays most H_2 used in industry is produced by steam reforming of natural gas or other hydrocarbons [13–15].

Many studies have been found in the literature regarding steam gasification of biochar derived from biomass. He et al., performed a study in a cyclone furnace on air-steam gasification of biochar produced through fast pyrolysis of ramie residues at 500 °C. Authors reported that higher equivalent ratio (ER) and optimum steam input led to higher dry gas yield, hydrogen yield, and carbon conversion efficiency. However, the hydrogen yield obtained in the referred work was very low (19.25 mmol·g^{-1}). Under the optimum experimental conditions (ER = 0.36, S/C = 0.45), the tar-free gas yield reached was of 3.72 N m^3·kg^{-1}, and its LHV was of 4163 kJ·N m^{-3} [9]. Zhai et al., investigated the characteristics of steam gasification of char from rice husk in a drop-tube furnace. Their results showed that temperature is the primary factor that influences the steam gasification reaction of rice husk char. Carbon conversion rate increases significantly (from 27.7% to 90.73%) with an increase in temperature from 700 to 950 °C. Moreover H_2 accounts for 46.9% (mol/mol) of the gas product at 950 °C [16]. Waheed et al., reported a H_2 yield of 100.97 mmol·g biochar^{-1} for non-catalytic gasification of biochar from the sugarcane bagasse at 950 °C [7], while Yan et al., obtained a H_2 yield of 57.07 mmol·g biochar^{-1} for the non-catalytic gasification of biochar from Pinus wood at 850 °C in a fixed-bed reactor. Both authors reported an increase in hydrogen volume fraction (29.54–52.41% on a dry basis) with increasing temperature (600–850 °C) as a result of further cracking at 850 °C. In the work of Yan et al., the highest dry gas yield was 2.44 N m^3·kg^{-1}, carbon conversion efficiency was 95.78%, and such results were obtained using a steam flow of 165 g·min^{-1} kg^{-1} biochar [17].

However, most studies have not focused on the reaction rate throughout the gasification process, and only few studies have addressed the reaction rate throughout the steam gasification of biochar [18–20]. A detailed knowledge on the gasification reaction behavior is paramount for process design and economic analysis on a commercial scale. Furthermore, one of the key challenges for commercial large-scale application of biochar in steam gasification processes is the application of other pyrolysis products, especially bio-oil. Perondi et al., investigated the reaction rate of steam gasification of biochar derived from poultry litter in a fixed-bed tubular reactor at different temperatures (800, 850 and 900 °C). According to the authors, the maximum hydrogen reaction rates were observed around the first 15 min of the reaction. Furthermore, authors reported a change in the maximum reaction rate towards lower reaction times with increased temperature [21].

In the available literature, there are no reported studies on reaction rates of steam gasification of biochar from elephant grass. Taking into account the advantages of elephant grass as a source of renewable energy (rapid growth, uncomplicated planting, low cost of planting and maintenance), the main objective of this study, and its innovative aspect, is to evaluate the reaction rate behavior and the influence of biochar properties from elephant grass throughout the steam gasification, with the intention of providing experimental data that may, in the future, assist in the design of industrial scale gasifier and its economic analysis. In addition, the present study also looks to the other products generated in the elephant grass pyrolysis process, in order to contribute to the gasification process scaling-up.

2. Materials and methods

2.1. Feedstock and characterization

Elephant grass used for biochar production was planted in a rural unit of Caxias do Sul University (geographic coordinates −28°81′44.13 −51°42′55.94). The biomass was grown for four months. It was milled in a knife mill to obtain particle size of 19 mm and dried in an oven at 105 °C for 8 h.

Biochar was produced using intermediate pyrolysis. It was carried out with approximately 1 kg of sample in a screw reactor at 400, 500 and 600 °C. Experiments at 500 °C were performed in triplicate. The rotary speed was 0.169 rpm, resulting in a solids residence time of approximately 33 min. A complete description of the reactor was given elsewhere [22]. Biochar and bio-oil yields (Y) were determined in accordance to Eq. (1).

$$Y(\%) = \frac{w}{w_0} \times 100 \quad (1)$$

where w_0 is initial mass of elephant grass fed into the reactor (g) and w is mass of biochar or bio-oil obtained after pyrolysis reaction (g). Non-condensable gas yield was calculated by difference.

The ultimate analysis and proximate analysis of biomass and biochars were carried out according to ASTM D5373/02 and ASTM 1762, respectively. The aromaticity (f_a) is associated with the amount of aromatic C present in the biochar. Models have been proposed to estimate the biochar aromaticity according to its elemental composition and its immediate analysis. Brewer et al., reported a correlation between biochar aromaticity and its respective contents of fixed carbon (FC) and volatile matter (VM), according to Eq. (2) [23].

$$f_a = 1.08\left(\frac{FC}{FC + VM}\right) + 0.02 \quad (2)$$

Wang, Camps-arbestain, and Hedley, evaluated 3 models to estimate the biochar aromaticity (f_a). The model that presented the best fit to the experimental data is based on ultimate analysis, being represented by Eq. (3) [24]:

$$f_a = -0.3864(H/C)^2 - 0.0292(H/C) + 0.9929 \quad (3)$$

Biomass (elephant grass) and their respective biochars characterization are presented in Table 1.

Elephant grass thermal analysis (TGA/DTG) was carried out in a Shimadzu thermobalance (TG-50 model) under inert atmosphere (N_2)