Energy for Sustainable Development 24 (2015) 50–57

Contents lists available at ScienceDirect

Energy for Sustainable Development

Determination of processes suitable for cotton stalk carbonization and torrefaction by partial combustion using a metal kiln

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ARTICLE INFO

Article history:
Received 19 October 2013
Revised 4 December 2014
Accepted 4 December 2014
Available online 20 December 2014

Keywords:
cotton stalks
carbonization
torrefaction
partial combustion

ABSTRACT

In this work, the technical feasibility of cotton stalk carbonization and torrefaction was studied. A metallic homemade cylindrical furnace 60 cm in diameter and 90 cm in height was used for the experiments. A partial combustion process was used both for carbonization and torrefaction. Three carbonization methods were defined based on the amount of air supplied and cotton stalks introduced in the kiln. Torrefaction process was based on a shorter combustion time of 2 min during the partial combustion, in order to avoid cotton stalk carbonization. Mass and energy yield, proximate analysis and the unburnt cotton stalks proportion (ratio of non-carbonized cotton stalks over carbonized cotton stalks) for each process were determined. In order to avoid the burning of the loaded cotton stalk, and to optimize charcoal quality, an appropriate combustion time of 7 min was found for the carbonisation process. The anhydrous mass yield for the best carbonization process selected is about 28.4% while energy yield is 45.8%. The carbonized cotton stalk has 24.15% and 67.44% of volatile matter and fixed carbon content respectively. The carbonized cotton stalks are suitable for cooking purpose because their volatile matter content allows a rapid ignition. The torrefaction process has a mass and energy yields of 64.1% and 75.3% respectively. Torrefied cotton stalks are more appropriate for gasification compared to carbonized cotton stalks.

Introduction

In West African countries, particularly in Burkina Faso, the majority of households use wood and wood charcoal for cooking. Ouedraogo (2006) noted that in Ouagadougou, the largest city of Burkina Faso, 76.3% of households use charcoal and wood for cooking energy. Fuel wood has become scarce in many countries. In this context, energy recovery from agricultural residue and other biomass resources is of great interest. Fuel wood has been replaced by agricultural waste and animal manure for household cooking use in large parts of developing countries of Asia. For cotton producing countries like Burkina Faso, a partial substitution of wood fuel by cotton stalks is of great interest.

The partial substitution of wood charcoal with cotton stalks can be done by the carbonization or the torrefaction of raw cotton stalks. Carbonization of biomass has been studied for several decades due to the extensive use of charcoal as an energy source in most developing countries. Charcoal has many other applications in metallurgy, soil amendment,… (Antal and Gronli, 2003). Regarding torrefaction, there is a renewed of interest in recent years because of its impact on improving biomass properties and on increasing the efficiency of the thermal conversion processes. Torrefied biomass has usually better physical and thermal properties (HHV, humidity,..) than raw biomass. Recent results have shown that torrefaction is a promising pretreatment for combustion, gasification and co-gasification of agricultural residues and coal since (Chen et al., 2012; Deng et al., 2009; Prins et al., 2006). Although several investigations on wood carbonization and torrefaction are available, a limited number of studies has been devoted to the carbonization and to the torrefaction of agricultural residues, especially to those of cotton stalks. It is established that conventional solutions of carbonization or torrefaction for wood are unsuitable for agricultural residues such as cotton stalks (Girard and Napoli, 2005).

Carbonization and torrefaction of the biomass are usually done by partial combustion and by direct or indirect heating. In this study a partial combustion is used for carbonization and torrefaction of cotton stalk. Note that, the use of the partial combustion for torrefaction is a new approach, as opposed to carbonization, since biomass torrefaction processes are usually done by direct and indirect heating (Basu, 2013).

However, carbonization and torrefaction lead to mass and energy losses. Consequently, only a fraction of the mass and energy are stored in the resulting solid residue after the carbonization or the torrefaction

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http://dx.doi.org/10.1016/j.esd.2014.12.003
0973-0826/

of the raw biomass. For carbonization process, the stored energy varies from 36 to 52% (Schenkel et al., 1998). Torrefaction mass and energy stored are about 70% and 90% respectively (Van der Stelt et al., 2011). Another fundamental parameter is the reaction cycle time of the carbonization as it largely determines the work load needed and the economic profitability of the process (Lin, 2006). The more the carbonization reaction cycle is lower, the more the produced charcoal and the gain are important. At least 7 days of reaction cycle time is required for conventional carbonisation process (Lin, 2006). Therefore, optimization is necessary to minimise mass and energy losses and to reduce reaction cycle time.

The objective of the present work is to determine processes of carbonization and torrefaction by partial combustion, suitable for cotton stalks, optimizing the reaction cycle time and the mass and energy yields. In this work a small homemade metal reactor was used for cotton stalks carbonization and torrefaction. The reactor has a cylindrical form, an air inlet at the bottom and a chimney. The device is simple, portable and can be used by farmers in field production. Three carbonization processes of cotton stalks were defined based on the amount of air supplied and cotton stalks introduced in the reactor. A fourth process was tested for cotton stalks torrefaction. For each process, the charcoal and unburnt cotton stalks masses, humidity, higher heating value (HHV) and proximate analysis of residues (charcoal and torrefied cotton stalks), the reaction cycle time were determined. Mass and energy yields were then calculated from these data.

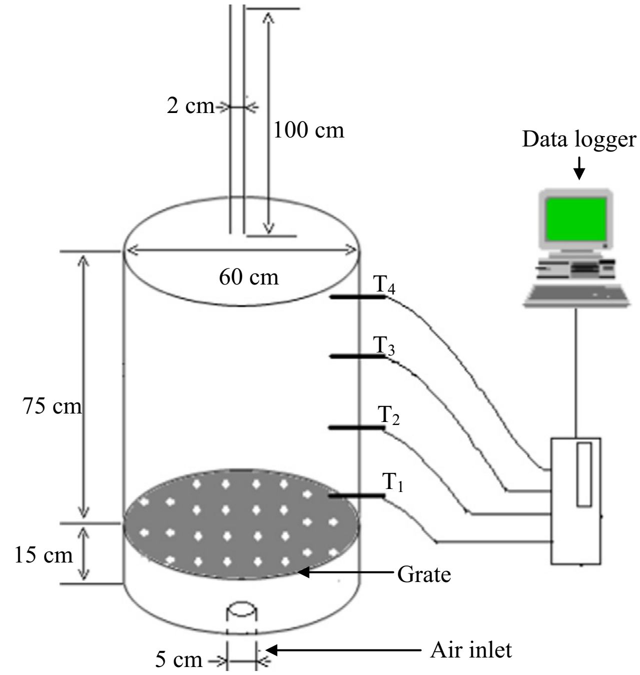

Fig. 2. Schematic diagram of the experimental setup.

Materials and methods

Materials

Figs. 1 and 2 show respectively the experimental apparatus and schematic diagram of the experimental setup. The apparatus includes a cylindrical metal reactor with a capacity of 0.25 m^3. A grate is set at 15 cm above the bottom of the reactor. The grate presents a total of 237 holes of 1 cm diameter. The reactor comprises a chimney with a height of 1 m and an inner diameter of 2 cm. The chimney is located at the centre of the metal lid of the reactor. Sealing is achieved by introducing water in a throat where the lid is placed on the reactor. An air inlet with a diameter of 5 cm is placed at the reactor bottom centre.

Temperature probes were placed laterally at 5 cm from the reactor inner surface (Fig. 2). Temperature data acquisition was done through four thermocouples of type K. The first thermocouple was placed 3 cm above the grid. The other three thermocouples were evenly spaced by 18 cm. The thermocouples were connected to a Gartner IDL101data logger. The acquisition frequency was set at 1 s. These data were transferred to a computer for further treatments.

Fig. 1. Experimental apparatus.

An analytical balance (precision of ± 10 g) was used for measuring the masses of cotton stalks and residues of processes. An HERMET oven type and a GALENKAMP bomb calorimeter were respectively used for the determination of moisture content (h) and higher heating value (HHV) using the standard given by XP CEN/TS 14774-3 (2005) and XP CEN/TS 14918 (2005). Proximate analysis was performed using a Heraeus muffle furnace following the standards given by XP CEN/TS 14775 (2005) and XP CEN/TS 15148 (2006). Ultimate analysis was performed according to XP CEN/TS 15104 (2005) and ASTM D5373-02 (2007) standards.

Experimental procedure

The cotton stalks were cut into pieces of maximum length of 30 cm. The cutting aims to allow the introduction of the cotton stalks into the reactor which has an inner diameter of 60 cm. The maximum capacity of the reactor is about 8 kg of cotton stalks. The sequence of operations leading to the carbonization is as follows (Fig. 3a, b, c, d, e, f): a 100 g weight of cotton stalks charcoal is burnt until it becomes red-hot and 1 kg of cotton stalks is introduced into the reactor. After ignition of this mass of cotton stalks, the remaining cotton stalks are introduced into the reactor. This causes inflammation of the whole load. Several quantities of cotton stalk ranging from 7 kg to 15 kg (quantity related to the process implemented) were added to the ignited load. At the end of the filling, combustion is maintained during a given time. The time between the end of filling and the closing of the reactor was called the combustion time. Cotton stalk combustion is ignited and developed during the filling and the combustion time. A chronometer is used to measure the combustion time. The reactor was closed and water was poured in the throat for sealing. Thus the combustion is quickly quenched and the reactor cools down. Based on this method, four processes are defined by varying the parameters of the process as described below.

The reaction cycle is defined as the overall carbonization or torrefaction process. It starts with the reactor filling and ends at its cooling down. The reaction cycle begins by a sensible temperature increase and ends when temperatures are less than 50 °C. This reaction