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

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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 Fuel wood has been replaced by agricultural waste and animal manure for household cooking use in large parts of developing countries of Asia.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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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.

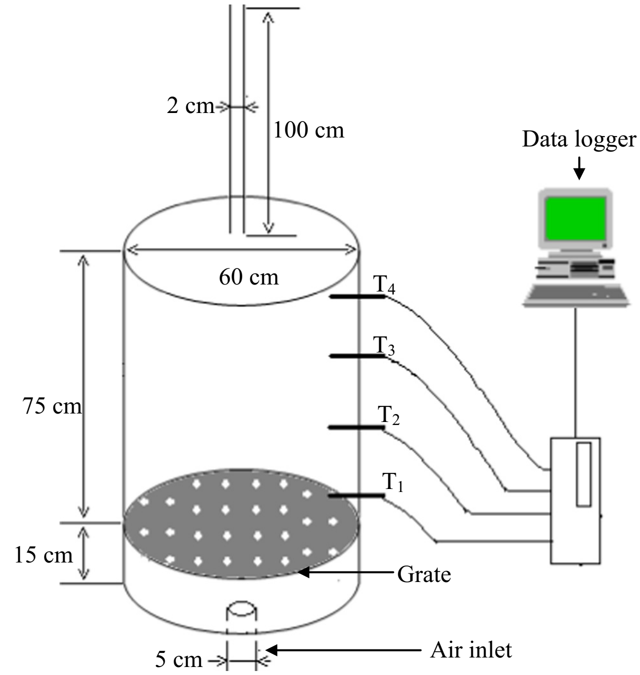

Fig. 2. Schematic diagram of the experimental setup.

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

Fig. 3. Description of the stages of carbonization: (a) chopped cotton stalks, (b) end of filling of the reactor and the beginning of the combustion time, (c) reactor closing and end of the combustion time, (d) sealing by introduction of water into the throat, (e) smothering of the combustion and cooling the charcoal, (f) cotton stalks charcoal.

cycle can be divided into two phases: the first phase covers the steps of ignition and combustion followed by carbonization (or torrefaction) before covering the reactor with the lid. The second is mainly the reactor cooling step. The first phase was called the carbonization or torrefaction step according to the process (carbonization or torrefaction). This phase is divided in two steps: cotton stalks filling and combustion.

Air supply, combustion time and quantity of cotton stalks are the operating parameters considered in the present study. Since the method is based on partial combustion of the loaded cotton stalks, combustion time plays a key role. A very short combustion time is expected to produce partially charred cotton stalks which can be assimilated to torrefied biomass. Very long combustion time will lead to the combustion of a large amount of cotton stalks. For this reason, a study of the influence of combustion time on the mass and energy yields of carbonization process was first conducted in order to estimate the combustion time which maximised the charcoal yield and quality. The maximum combustion time of 10 min was set in order to avoid excessive combustion of the cotton stalks since the quantity of used cotton stalks is small (16 kg maximum). Shortest combustion time was fixed to 2 min in order to avoid charring of the cotton stalks and to produce torrefied cotton stalks (partially carbonized cotton stalks). Intermediate combustion time of 5 and 7 min were also used for trials.

In order to reduce the number of trials, the impact of combustion time on carbonization processes was first analysed. For this purpose carbonization trials were done according to Process 1, described below. Thus the optimum combustion time was determined and used for the carbonization processes investigated in this study. Three processes of carbonization and one of torrefaction were investigated, as described below.

Process 1

7 kg of cotton stalks are introduced in the reactor; the air inlet is opened during the process. Thus this process is done with air supply at the reactor bottom.

Process 2

7 kg of cotton stalks are introduced in the reactor; the air inlet is closed. During the carbonization, cotton stalks have contact with air only when the lid is opened. This process is conducted without air supply at the reactor bottom.

Process 3

15 kg of cotton stalks are introduced in the reactor. Although the capacity of the reactor is 8 kg, the gradual reduction in the fuel bed level had made possible the continuous addition of cotton stalks. Air inlet is closed, thus this method is done without air supply at the reactor bottom.

Torrefaction

7 kg of cotton stalks are introduced in the reactor. Air inlet is closed and the combustion time is fixed at 2 min. This torrefaction process is different from most of the torrefaction processes encountered in the literature. Torrefaction is usually done in a neutral medium by heating walls or by using hot smoke (Basu, 2013; Sridhar et al., 2007; Patel et al., 2011). The present process involves the partial combustion of a small portion of the load, while the remainder of the load is torrefied. Thus, this method is autothermal, very simple and does not require complex technology.

For all processes the trials were replicated three times. The influence of these operating parameters on the reaction cycle time, mass and energy yield of carbonization was studied. The partially carbonized cotton stalks during the carbonization processes are called unburnt cotton stalks. The term "unburnt material" was used by Mlaouhi et al. (1999), however other authors used the term "partially carbonized material" (Patil et al., 2000). Unburnt cotton stalks are manually separated with charcoal. Weight of unburnt cotton stalks was not considered in mass and energy yield calculation of carbonization processes. The reaction cycle time was determined on the basis of temperature profiles.

Table 1
Results of the proximate analysis and HHV of cotton stalks.

HHV (MJ/kg)	*Humidity* (%, ar[1])	*Ash* (%, db[2])	*Volatile Matter* (%, db)	*Fixed Carbon* (%, db)
19.13	13.23	4.06	76.60	19.34

[1] ar : as received basis
[2] db : dry basis

Table 3
Influence of combustion time on carbonised cotton stalks proximate analysis (dry basis).

Combustion time (min)	*Ash* (%)	*VM* (%)	*FC* (%)
5	8.02	29.78	62.20
7	9.94	25.81	64.25
10	10.69	20.69	68.62

Results and discussion

Impact of carbonization combustion time

Raw cotton stalk properties are given in Table 1. For a given combustion time studied, the reaction cycle time, the cotton stalk filling time, the mass and energy yields, the proportion of unburnt cotton stalks and the proximate analysis data, the peak temperature and the average temperature are given in Tables 2 and 3). The mass yield, η_m (dry basis), is given by the ratio of the net mass of dry residues over the dry raw cotton stalk mass as defined by Eq. (1), where m, m_{ig}, M, $h_{residue}$, $h_{cotton\ stalk}$ are respectively the residues (charcoal or torrefied cotton stalks) mass, the mass of residues used for ignition, the raw cotton stalks mass, the moisture content of obtained residues and the moisture content of raw cotton stalks.

$$\eta_m = 100 \times \frac{m(1-h_{residue})-m_{ig}}{M(1-h_{cotton\ stalk})} \quad (1)$$

The energy yield, η_e, is given by the ratio of the net energy output over the input energy as defined by Eq. (2), where $HHV_{residue}$, HHV_{ig} and $HHV_{Cotton\ stalk}$ are respectively higher heating value of residues, residues used for ignition and raw cotton stalk.

$$\eta_e = 100 \times \frac{HHV_{residue} \times m(1-h_{residue})-m_{ig}HHV_{ig}}{HHV_{Cotton\ stalk} \times M(1-h_{cotton\ stalk})} \quad (2)$$

The unburnt cotton stalks rate ($\eta_{unburnt}$) is used to characterize the percentage of the mass of unburnt cotton stalks with the mass of obtained carbonized cotton stalks. The highest temperature during carbonization is usually defined as peak temperature. In this study, the peak temperature (T_{max}) is defined as the average of the highest temperature reached in the reactor for the three replicated trial for a given combustion time. The average temperature (T_{av}) represents the mean temperature over the combustion step.

Combustion phase provides the energy needed for cotton stalk drying and carbonization. When cotton stalks are combusted for a long time, an excess of energy is produced compared to the energy required for carbonization process. Thus, increasing combustion time leads to a decrease in mass and energy yields and the proportion of unburnt cotton stalks. For the combustion times in the range from 5 min to 10 min, the peak and the average temperatures increase contrary to the unburnt cotton stalks rate which decrease.

The charcoal produced by carbonization with long combustion time is more homogenous due to the absence of unburnt cotton stalks. Differences in charcoal HHV are not significant for all combustion time used in this study. However some differences appear in charcoal proximate analysis results. Increasing the combustion time leads to a decrease in the volatile matter content (VM) which consequently increases the ash content (Ash) and fixed carbon (FC) of charcoal. The improvement of charcoal quality (FC) is probably the result of the increase of the peak temperature (Tables 2 and 3). This result is consistent with other works in the literature (Antal and Gronli, 2003; Schenkel et al., 1998). Physical appearances are also affected by combustion time. Indeed charcoal obtained with increasing combustion time is more friable and lighter.

Charcoal obtained with 5 min combustion time has the highest VM content. This VM content will be more important if unburnt cotton stalks are considered in charcoal yield. Charcoal quality and its economic value will decrease because of smoke release during mixture of unburnt cotton stalks and charcoal combustion. Taking into account the results for the three combustion times studied, it appears clearly that there is an improvement in the quality and homogeneity of charcoal (regarding HHV, FC and unburnt cotton stalks rate) when the combustion time increases. However, this improvement in the quality of charcoal should not be achieved at the expense of a significant drop in the mass and energy yield of carbonization process. Therefore, combustion time of 7 min achieves the best compromise. This combustion time (7 min) has been used for all carbonization processes defined in this study (Process 1, 2 and 3).

Description and duration of the different phases of the processes

Fig. 4 shows the temperature profiles in the reactor. These profiles allow identification of the different phases of carbonization and torrefaction.

The temperature profiles have a similar overall trend (Fig. 4). The profiles are similar to those obtained by Saravanakumar et al. (2006) and Mlaouhi et al. (1999). Fig. 4a presents the two phases of the reaction (1 and 2). In the first phase, temperatures increase quickly to reach a maximum value, which characterizes the cotton stalk rapid ignition. Ignition fluctuations cause usually an oscillation of temperature profiles during reactor filling. After ignition and filling, cotton stalks combustion occurs mainly during the fixed combustion time. The heat from combustion leads to the carbonization or torrefaction of the loaded mass of cotton stalks. Thus, carbonization or torrefaction of cottons stalks takes place during the first phase. Cotton stalk ignition occurred mainly during the filling step. In the second phase, the reactor cooling down is characterized by a sudden temperature drop which happens when the reactor is closed. Slight overpressure is observed during nearly 10 min at the beginning of the cooling phase during smothering. The mean times for these phases are given in Table 4 for the four processes.

For cotton stalks, the carbonization phase takes place very quickly in comparison to wood. The first phase of carbonization process varies from 15 min to 25 min and that of the torrefaction is reduced to 7 min. Process 3 has a filling time twice that of other processes,

Table 2
Impact of combustion time on carbonization process and charcoal proximate analysis.

Combustion time (min)	*Reaction cycle time* (min)	*Filling time* (min)	*HHV* (MJ/kg)	η_m (%, db)	η_e (%)	$\eta_{unburnt}$ (%)	T_{max} (°C)	T_{av} (°C)
5	120	7.7	29.23	23.9	35.8	17.5	660	370
7	150	7.7	30.9	21.9	35.4	2.5	697	375
10	115	6.0	30.91	16.3	26.3	0	750	496

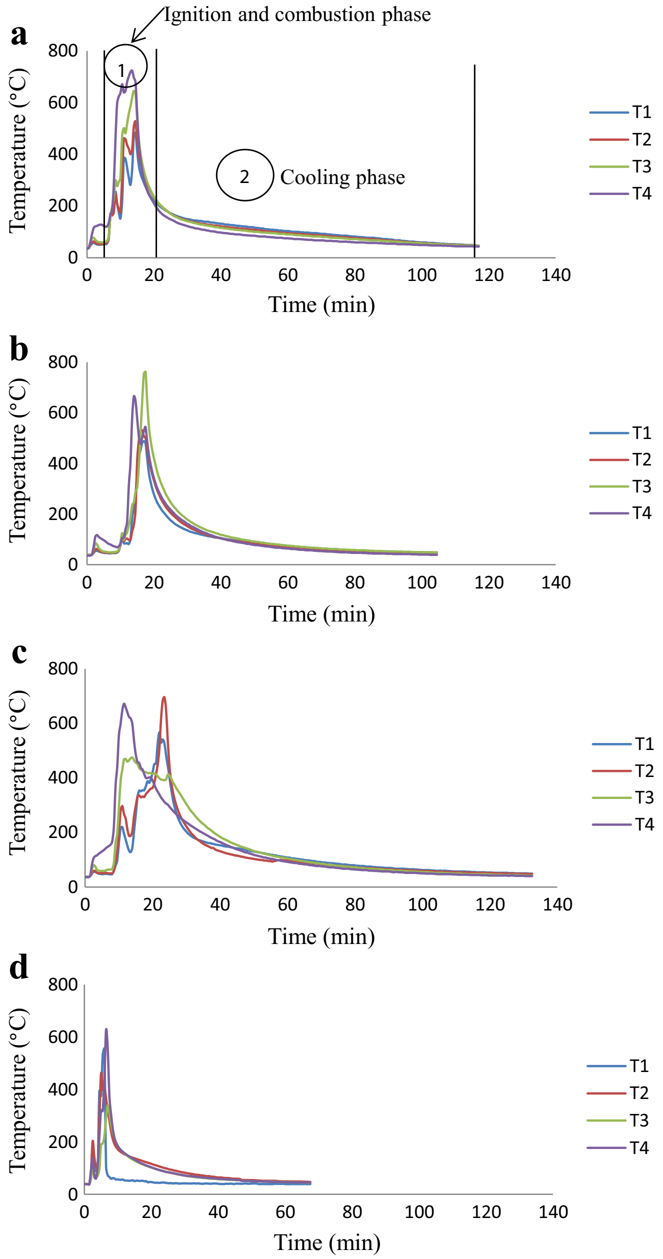

Fig. 4. Temperature variation depending on the process. (a): Process 1, (b): Process 2 , (c): Process 3, (d): Torrefaction process.

since cotton stalk mass used is double. For several wood species, Saravanakumar et al. (2006) obtained a carbonization phase duration ranging between 120 and 195 min. Carbonization phase takes nearly 45 minutes to 1 hour with drum carbonization process of agricultural residues (Wondwossen, 2010). This significant difference with our results is related to the combustion characteristics of cotton stalks and the processes used. Agricultural residues (such as cotton stalks) have higher volatile matter content and a higher devolatilization rate than wood (Werther et al., 2000). Devolatilization begins at low temperatures and occurs almost instantaneously as the residues are exposed to high temperature (Werther et al., 2000). Higher mass lost is achieved at 283 °C in oxidative environment comparatively to inert environment (Munir et al., 2009). This allows the flame to develop rapidly mainly at the top of the reactor. Table 5 summarises the mean peaks of the temperature at different locations of the reactor (from the bottom to the top) and time (at which peak temperature is achieved) for torrefaction and carbonization processes. Peak temperature is reached at the reactor top (T3 or T4) contrarily to the process of the carbonization of wood during which peak temperature is reached at the reactor bottom (Saravanakumar et al., 2006). The temperature peaks measured during this work for the carbonization processes ranged from 650 to 750 °C (Table 5). For torrefaction the temperature peak (498 °C) is lower due to short combustion time (only 2 min). The temperature peak of the carbonization of cotton stalks is higher than that of the carbonization of the wood but the fixed carbon content is lower in the char of cotton stalks in comparison to the char of wood because of the high ash content in cotton stalks.

Peak temperature is achieved in a very short time during the current processes relative to other process (Fig. 4). This could limit peak temperature impact on the product properties. Cotton stalks are exposed to elevated temperature for a short period of combustion time. Table 6 gives the amplitudes of the variation of the peak of temperature (difference of the peak temperature) inside the reactor and the average temperature of the combustion step. Average temperature of combustion step ranged from 369 °C to 393 °C for the three processes of carbonisation. This relatively low average temperature contributes to lower the fixed carbon content of the charcoal.

The reactor filling method has an influence on the temperature field. However, for processes 1, 2 and torrefaction the temperature profiles are similar. For these processes the cooling step in the entire reactor begins as soon as the reactor is closed. Therefore, all thermocouples reach their peak temperatures at practically the same time (Table 5). For process 3, peak temperatures at the reactor top and bottom is not achieved at the same time. The continuous filling with cotton stalks leads to temperature fluctuations, mainly at the reactor top when the temperature is growing at the reactor bottom. The consequence is that the peak temperature at different locations of the reactor is not achieved at the same time. Differences in the peak temperatures (ΔT) in the reactor is related to the process used (Table 6). These differences on the peak of the temperature are comparable to those obtained by Lin. (2006) for traditional carbonization processes.

Table 4
Mean duration of carbonization and torrefaction process phases.

Process	Duration of the carbonization or torrefaction step (min)	Duration of filling step (min)	Duration of the cooling step (min)
Torrefaction	7	5	65
Process 1	15	8	135
Process 2	16	9	104
Process 3	25	18	100

Table 5
Temperature peak and time at which peak temperature was achieved for torrefaction and carbonisation processes.

	Torrefaction		Process 1		Process 2		Process 3	
	Peak (°C)	t (min)	Peak (°C)	t (min)	Peak (°C)	t (min)	Peak (°C)	t (min)
T1	333	5.3	502	13.6	492	17.4	580	23.7
T2	469	5.7	520	14	499	17.4	600	24.5
T3	304	6.3	651	13.6	701	15.8	525	18.2
T4	498	6.2	621	13.6	667	15.9	751	17.2

Table 6
Peak temperature difference (ΔT) and mean temperature during combustion step of the torrefaction and carbonisation processes.

Process	ΔT (°C)	T_{av} (°C)
Torrefaction	194	322
Process 1	149	375
Process 2	209	369
Process 3	226	393

Table 7
Performance of three carbonization processes and torrefaction of cotton stalks.

Process	*Humidity* (%, ar)	*Reaction cycle time* (min)	*HHV* (*MJ/kg*)	η_m (%, db)	η_e (%)	$\eta_{unburnt}$ (%)
Process 1	4.00	150	30.90	21.9	35.4	2.5
Process 2	4.58	120	29.27	27.7	42.4	3.4
Process 3	3.49	125	30.83	28.4	45.8	0.5
Torrefaction	8.34	75	22.49	64.1	75.3	--

Table 8
Proximate analysis (dry basis) of charcoal and torrefied cotton stalks.

Process	*Ash* (%)	*VM* (%)	*FC* (%)
Process 1	9.94	25.81	64.25
Process 2	8.95	25.74	65.31
Process 3	8.41	24.15	67.44
Torrefaction	5.79	68.50	25.71

Note that the variations on the temperature peak inside the reactor have less impact on the heterogeneity of torrefied and carbonized cotton stalks than the variations of the time of combustion. Indeed, torrefaction has low peak temperature variation (194 °C) but torrefied cotton stalks are more heterogeneous due to low combustion time of torrefaction. During the combustion step of torrefaction, cotton stalk are exposed to an average temperature of 322 °C, slightly higher than temperature encountered in the literature (300 °C). This led to considerable heterogeneity for torrefied cotton stalk in comparison to most torrefaction processes where temperature is maintained for much more time (30 min to 3 hours).

Process performance

Process 1 has the lowest mass and energy yield and the longest cooling step duration (Tables 4 and 7). This low yield is due to the air supply. As can be seen from Fig. 5a, after each trial of process 1, there is a formation of ash on the grate.

The combustion of the charcoal is maintained in the lower part of the reactor. This explains the higher duration of the cooling of process 1 compared to the other processes (Table 4). Closing the air inlet results in the absence of ashes on the grate (Fig. 5b). There is therefore no excessive burning of the charcoal produced which leads to an increase in the yield of the mass and energy.

The mass yields are almost identical for the two processes for which the air inlet was closed (processes 2 and 3) as shown in Table 7. These two processes gave mass yields that are about 27% higher than the mass yield of process 1. The low mass yield for process 1 results in low energy yield. Therefore, in contrast to the results obtained by Saravanakumar et al. (2006) for the carbonization of wood, air supply at the reactor bottom is not suitable for cotton stalks in this type of reactor.

Lower unburnt cotton stalks and quite homogenous charcoal was obtained by carbonization process 3. This is due to a longer exposure of cotton stalks at high average temperature (393 °C) during the carbonization phase. Consequently, higher FC is obtained by the process 3 (Table 8).

Process 3 is most efficient because it leads to the lowest unburnt cotton stalks and the best energy yield. HHV of charcoals from different carbonization processes are quite close. Mass and energy yield for process 2 and 3 are similar, but process 3 results in more homogenous charcoal. Furthermore, process 3 produces twice as much charcoal than process 2 for practically the same reaction cycle time.

For a good charring unit, energy yield must be in the order of 60% (Girard and Napoli, 2005). Although the energy efficiency obtained in this work did not reach 60%, it is however higher than the energy yield of most traditional carbonization processes given by Schenkel et al. (1998). Criteria for charcoal quality are subjective; the quality depends mainly on the final use (Adetoyese et al., 2012). Charcoal quality is usually determined by its FC content. For cooking, VM is also taken into account since it should be sufficient to allow a rapid ignition. There is no significant difference between Ash, FC and VM of charcoals derived from process 2 and 3 (Table 8). Table 9 summarizes the characteristics of carbonization process 3 and the most efficient carbonization processes by partial combustion given by Schenkel et al. (1998). Based on the range of volatile matter content defined by Foley (1986) and FAO (1987) for domestic use of charcoal and the results of Table 9, both processes 2 and 3 give charcoal that could be used to substitute domestic wood charcoal.

Comparison in Table 9 shows that the optimum method of the present study (process 3) can be considered as one of the best carbonization processes by partial combustion. Anhydrous mass and energy yields of 28.4% and 45.8% respectively, are higher to those of most traditional carbonization processes. Considering torrefaction, the difference between the process developed in this study with those reported in literature makes comparison difficult. In addition, this process does not allow production of uniform torrefied cotton stalks (Fig. 6). This is not specific to this type of reactor. According to Basu (2013), only fluidized bed reactors can achieve a very uniform torrefied biomass. Energy and mass yields obtained for torrefaction process in the present study are respectively 75.3 and 64.1%. They are lower compared to those obtained in the literature for wood torrefaction. According to Van der Stelt et al. (2011), wood torrefaction allows conservation of 70% and 90% of the mass and energy of the initial biomass. The difference could be due to the carbonization of a part of cotton stalks

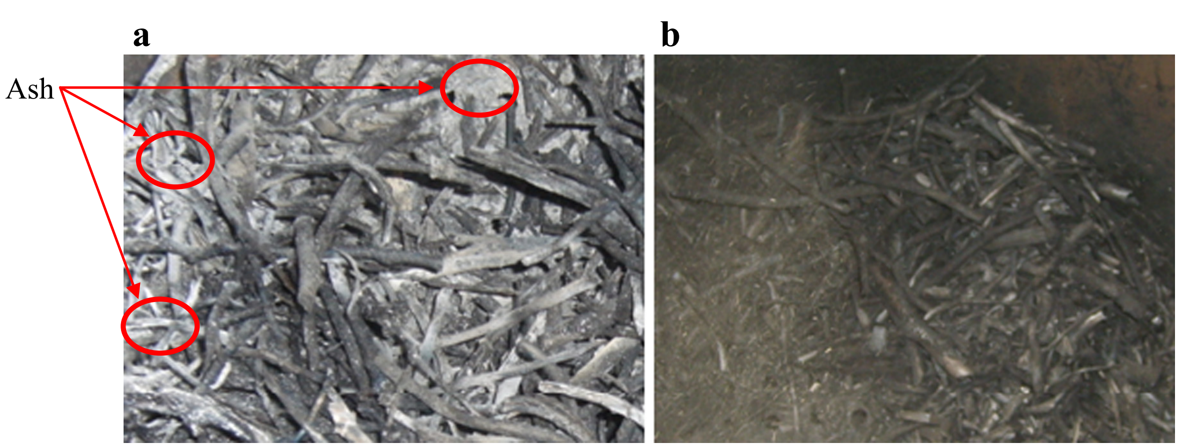

Fig. 5. Presence of ash on the grate after carbonization with air supply at the reactor bottom trial. (a) Process with air supply; (b) Processes without air supply.

Table 9
Performances of traditional carbonization process and optimum process of this study.

	Traditional process (Schenkel et al., 1998)	Process 3 of this study
Carbonization cycle time (h)	10-125	2
Humidity (%, ar)	12-56	13
Fixe carbon content (%, db)	58-88	67
Charcoal HHV (MJ/kg)	30-32	30.8
Charcoal mass yield (%,db)	12-32	29
Energy yield (%)	18-58	47

during the combustion phase of 2 min. In addition, torrefaction conditions can lead to a low energy yield especially for agricultural residues. During torrefaction process, the biomass components (cellulose, hemicelluloses and lignin) react at different degree depending on the nature of the raw biomass. Considerable differences are encountered for energy yield and properties of torrefied biomass in the literature. It has been proved that energy yield decreases when torrefaction temperature increases. In current torrefaction process, cotton stalks are exposed to average temperature of 322 °C during

Table 10
Ultimate analysis (dry ash free basis), O/C and H/C atomic ratio of raw cotton stalks, torrefied and carbonized cotton stalks.

Biomass	Raw cotton stalks	Torrefied cotton stalks	Carbonized cotton stalks
Ultimate analysis			
C (%)	47.62	53.13	76.47
H (%)	6.81	6.04	3.60
N (%)	0.51	0.57	1.07
O* (%)	45.05	40.26	18.86
O/C and H/C atomic ratio			
O/C	0.71	0.57	0.19
H/C	1.72	1.36	0.56

* obtained by difference

2 min of combustion time. This average temperature is higher than 283 °C which is the temperature when instantaneous cotton stalks mass lost is achieved (Munir et al., 2009; Werther et al., 2000). This can explain the large mass and energy lost observed in the present torrefaction process. Thus the current torrefaction process is

Fig. 6. Raw cotton stalk and residues from carbonization and torrefaction of cotton stalks by partial combustion. (a) Raw cotton stalk; (b) Torrefied cotton stalks; (c) Carbonized cotton stalks.

comparable to torrefaction conducted in severe conditions (temperature range from 275 °C to 300 °C). Indeed, in severe conditions energy yield ranged from 69% to 80% and HHV ranged between 22 MJ/kg to 24 MJ/kg for torrefied agricultural residues, (Patel et al., 2011; Rousset et al., 2011; Bridgeman et al., 2008). Low mass yield (20-60%) was obtained at 300 °C in oxidative environment for several agricultural residues (Chen et al., 2014). These mass and energy yields are comparable to those obtained during the present studies.

Ultimate analysis results, atomic ratio of O/C and H/C for raw materials, torrefied and carbonised cotton stalks are presented in Table 10. Torrefied products have VM of 68.5% against 76.6% for raw cotton stalks. This is consistent with results reported in literature for VM of torrefied biomass (Prins et al., 2006). Torrefaction increases the FC and Ash content of cotton stalks, from 19.34 to 25.71% and from 4.06 to 5.78% respectively. Carbon content of torrefied cotton stalk increased by 6 percentage points. The overall variation of carbon, hydrogen and oxygen are in the range of those reported by Bridgeman et al. (2008). Even though torrefied cotton stalks are heterogeneous, it may be useful for gasification at small scale in African rural areas. Indeed, reduction of VM due to torrefaction is expected to reduce tar content in gasification process. In addition, atomic O/C ratio is closed to 0.4, the optimum ratio for gasification as established by Prins et al. (2007). The obtained carbonized cotton stalk can also be used for gasification using air and steam mixture as oxidizing agent (He et al., 2012). However drastic mass loss during carbonization will lead to very low carbonization and gasification overall efficiency. Low mass loss compared to carbonization and device affordability may help to make viable final torrefied cotton stalks valorisation, mainly by small scale gasification.

Conclusion

This study has highlighted the potential of cotton stalks carbonization and torrefaction by partial combustion. The work focused on three carbonization processes and one torrefaction process. The combustion time, reaction cycle time, the mass and energy yields, the characteristics of charcoal and torrefied cotton stalks were analyzed. The suitable and the best carbonization process for cotton stalks, was obtained by continuous feeding of the reactor and by closing the air inlet. The mass and energy yields of 28.4% and 45.8% can respectively be achieved by this carbonization process. The reaction cycle time of 2 hours is obtained by this process. In addition, the charcoal obtained by the current carbonization process is of good quality and is useful for domestic use. The torrefaction of cotton stalks is successfully performed by fixing a short combustion time of about 2 minutes. Energy yield of 75.3% and HHV of 22.5 MJ/kg of torrefied cotton stalks have been obtained. The simplicity of the process allows the torrefaction and carbonization with limited means, especially in rural areas. These results are interesting for the development and improvement of the profitability of the cotton chains valorisation in Burkina Faso.

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