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Impact of pre-treatment by torrefaction and carbonization on temperature field, energy efficiency and tar content during the gasification of cotton stalks

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The present study focused on the gasification of raw and pre-treated cotton stalks (CS) by torrefaction and carbonization. Temperature fields, mass balance, energy balance, energy efficiency and tar content of the gas were investigated for the gasification of different types of biomass materials (raw, torrefied and carbonized CS). High temperature and thick reduction zone were obtained during the gasification of pre-treated CS comparatively to the gasification of raw CS. Thus, the thermal and catalytic cracking of the tars may be more pronounced for the gasification of pre-treated biomass particularly for the carbonized biomass. Mass and energy balances have shown a reduction of biomass conversion during the gasification of torrefied and carbonized CS. Indeed, the energy efficiency of 58.7, 46.5 and 38.4% were obtained for raw, carbonized and torrefied CS, respectively. The lowest energetic performances were found during the gasification of torrefied CS due probably to the severe degree of the torrefaction. However, the tar content in gas was drastically decreased by the pre-treatment of the CS. Indeed, the tar contents of 4.41, 2.24 and 0.10 g/Nm^3 were obtained for the gasification of raw, torrefied and carbonized CS, respectively.

Key words: Biomass gasification, pre-treatment, tar content, energy efficiency.

INTRODUCTION

West African countries are faced with lack of access to modern energy such as electricity which can compromise their economic development (Ouedraogo, 2013). In the case of Burkina Faso, the electricity production policies must consider the energy sources such as agricultural residues as cotton stalks in order to ensure economic growth (Ouedraogo, 2010). Burkina Faso is a great African cotton producer with a production estimated at

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768 930 ton of cotton in 2016 (INSD, 2016). Thus, the cotton stalks (CS) can be converted into gas by the gasification technology for electricity production. A downdraft gasifier is particularly adapted for this purpose since it produces less dirty gas comparatively to other gasification technologies. The limit of the gasification is related to the gas quality. Generally, the produced gas contains significant amounts of tar which condense at low temperatures, leading to mechanical problems in the engines and in the turbines. Removing of tar from the gas causes a considerable increase of the kWh production cost as a result of investment in the gas scrubber. The volatile matter content of the biomass is at the origin of tar formation during the gasification. Reducing volatile matter content of raw biomass could reduce the tar content of the gasification gas. Torrefaction and carbonization reduces the volatile matter content and this process can be implemented easily in rural areas. It should be noted that the research results on tar production during the gasification of torrefied or carbonized biomass are scarce. Wannapeera et al. (2011) have suggested that torrefied woody biomass produces less tar at pyrolysis stage than raw biomass. Consequently, this can lead to the reduction of tar content during gasification. Dudyński et al. (2015) have shown that the gasification of torrefied biomass produces less tar content than raw biomass. This fact was confirmed by the results obtained by Di Marcello et al. (2017). The tar reduction may be due to the devolatilization of volatile matter undergone by torrefied biomass and the high temperature achieved during the gasification of torrefied biomass which favoured the thermal cracking of the tar. Experimental study on gasification of torrefied and carbonized cotton stalk are non-existent in the literature. In the present work, the carbonization and torrefaction have been considered as pre-treatment methods to reduce the tar content during the gasification of cotton stalk. In addition, torrefaction and carbonization could improve energetic performances during biomass gasification. In this context, thermodynamic equilibrium model was used by Kuo et al. (2014) to study the gasification of raw bamboo and torrefied bamboo at 250 and 300°C with air and steam as gasification agent. They found an increase in the gas yield depending on the torrefaction temperature, contrary to the conversion of carbon which decreased. Study on the gasification of torrefied tomato peels conducted by Brachi et al. (2018) also shown the decrease of carbon conversion and a modest improvement of lower heating value of the gas. The carbon conversion decrease may be due to the decrease of the reactivity of char resulting in the torrefied biomass as reported by many studies (Karlström et al., 2015; Fisher et al., 2012; Jones et al., 2012). As a consequence, the energy efficiency of the gasification of torrefied biomass can decrease when the biomass is torrefied in severe conditions. Indeed, gasification of torrefied bamboo in medium conditions (at 250°C) gave the best results for energy efficiency and LHV of the gas than the gasification of torrefied bamboo in severe conditions (at 300°C) (Kuo et al., 2014). A similar result was found for the gasification of torrefied wood residues (Weiland et al., 2014). The gas LHV and the energy efficiency decrease have also been reported during the gasification of torrefied switch grass at 250 and 270°C comparatively to the raw switch grass (Sarkar et al., 2014).

The objective of the present work is to study the impact of torrefaction and carbonization on the temperature fields, performances by the mean of mass and energy balances of the gasification of cotton stalks and the tar content of the producer gas.

MATERIALS AND METHODS

Biomass characteristics

The raw cotton stalk biomass feedstock was collected in the province of Léo in Burkina Faso. The raw, torrefied and carbonized CS were used as biomass feedstock in the present study. Table 1 gives the proximate and ultimate analysis and HHV of these different types of biomass (Harouna et al., 2015).

Torrefied and carbonized CS were obtained by a partial combustion method using a metal kiln. This method allows the production of highly heterogeneous torrefied CS which was assimilated to torrefied biomass in severe conditions. A manual crusher was used to cut the raw, the torrefied and the carbonized CS at a maximum size of 4 cm in order to allow the reactor feeding (Figure 1).

Gasifier apparatus and process

The experimental setup and the schematic of the gasification are presented in Figure 2. The reactor insulation was improved by a double wall with the gap filled with rice husk carbon free ash. The reactor was separated with the ash collector by a square grate of 20 cm of length. The grate was shook each 20 min in order to facilitate the ash evacuation.

Air was supplied with a centrifugal blower connected at the inlet, located at the top of the reactor. A granular filter and a flare were located at the exit of the gasifier. As shown in the diagram, the gasifier was instrumented with six thermocouples of type K to measure the temperature throughout the reactor. Five of them were placed laterally at 2 cm from the reactor inner surface. They were evenly spaced by 10 cm. The sixth thermocouple was installed under the grid (in the ash collector) to measure the temperature of the gas. An analytical balance (precision of ± 10 g) was used to weigh the masses of biomass materials which were introduced in the gasifier. The sampling train is presented by Figure 2b. Continuous sampling of the gas was carried out during the gasification trials. A simplified gas sampling train was designed and realize based on the standard (CEN/TS 15439, 2006). The reactor external wall and the cold bath temperature were noted regularly.

Three gasification experiments were defined according to the type of the biomass (raw, torrefied and carbonized CS) used. The blower inlet surface was fixed during the gasification trials. This allowed the realisation of the gasification trials with a small variation of the air flow. Thus, the present study is not focused on the optimization of energetic performances which would necessitate the air flow variation. Three trials were conducted for each type of feeding biomass. More details on the apparatus and the gasification

Table 1. Characteristics of raw, torrefied and carbonized CS.

Biomass	Raw CS	Torrefied CS	Carbonized CS
Ultimate analysis (%)			
C	47.62	53.13	76.47
H	6.81	6.04	3.60
N	0.51	0.57	1.07
O[1]	45.05	40.26	18.86
Proximate analysis (%)			
Humidity	13.23	8.34	3.49
Ash (db[2])	4.06	5.79	8.41
Volatile matter (db)	76.60	68.50	24.15
Fixed carbon (db)	19.34	25.71	67.44
High heat value (MJ/kg)			
HHV	19.13	22.49	30.83

[1]O(%): Obtained by difference; [2]db: dry basis.

Figure 1. Biomass feedstock. (a) RAW CS, (b) torrefied CS, (c) carbonized CS.

method are available elsewhere (Harouna et al., 2017).

Mass balance

The mass balance was evaluated for the different trials. Equation 1 gives the mass balance of the gasification.

$$m_b + m_{air} = m_{gas} + m_r \quad (1)$$

Where, m_b, m_{air}, m_{gas} and m_r are the mass of biomass, air, gas and residues, respectively. The tar content was not considered in the mass and energy balances since it is usually small. The mass of water vapour contained in the producer gas was not determined. The mass of the biomass and the residues were weighed before and after the gasification trials. The residues were composed by ash and residual carbon (unconverted). The mass of air was calculated by considering the density (ρ_{air}) in normal condition and the normal volume of air (V_{air}), (Equation 2). T_0 and P_a are the normal temperature and the atmospheric pressure. T_a and M_{N_2} are the mean ambient temperature and the molar mass of nitrogen.

$$m_{air} = \rho_{air} V_{air} T_0 / T_a \quad (2)$$

Nitrogen conservation during the gasification process was used for the calculation of the gas volume according to Equation 3. $[N_2]_{air}$ and $[N_2]_{gas}$ are respectively, the nitrogen volume fraction (%v) in air and gas. $\rho_{N_2}(T_a)$ and $\rho_{N_2}(T_{gas})$ are respectively, the nitrogen density at the ambient temperature and gas temperature (T_{gas}) as given by Equation 4.

$$V_{gas} = \left[\rho_{N_2}(T_a)[N_2]_{air} / \rho_{N_2}(T_{gas})[N_2]_{gas}\right] \times V_{air} \quad (3)$$

$$\rho_{N_2}(T) = M_{N_2} P_a / RT \quad (4)$$

The mass of gas was calculated considering the molar number of the produced gas, given by the ratio of the gas volume and the molar volume (V_m), the volume fraction ($[i]_{gas}$) and the molar mass (M_i) of the gas species (i) according to Equation 5. Molar

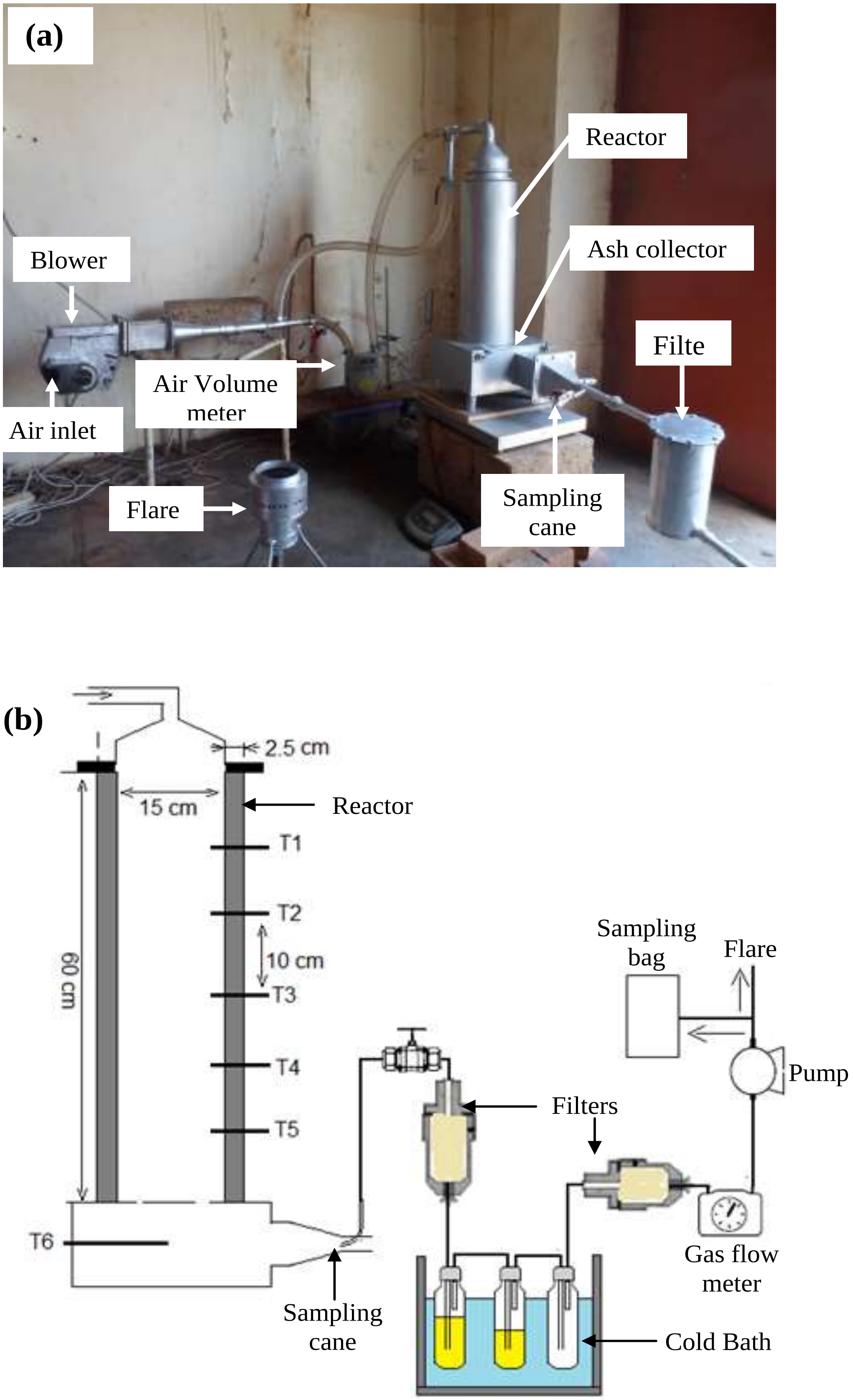

Figure 2. Experimental devices: (a) Experimental setup and (b) schematic diagram of the gasification system.

volume of gas at temperature (T) was given by ideal gas equation of state (Equation 6).

$$m_{gas} = \left(V_{gaz}/V_m\right) \sum_{i=1}^{5} [i]_{gas} M_i \quad (5)$$

$$V_m = RT/P_a \quad (6)$$

Energy balance

The energy balance involved the energy input, output and lost during the gasification trials as given by Equation 7.

$$E_b + E_{air} = E_{gas} + E_r + E_{wall} \quad (7)$$

E_b, E_{air}, E_{gas}, E_r and E_{wall} were respectively the energy content in biomass, air, gas, residues and lost through the reactor wall. The energy content of biomass, air and gas were computed by Equations 8 to 10, respectively.

$$E_b = m_b \left[\left(1 - t_{h_b} - t_{ash}\right)\left(LHV_b + c_{p_b}(T_a - T_0)\right) + \left(t_{ash} c_{p_{ash}} + t_{h_b} c_{p_{water}}\right)(T_a - T_0)\right] \quad (8)$$

$$E_{air} = n_{O_2}\left[h(T)_{O_2} - h(T_0)_{O_2}\right] + n_{N_2}\left[h(T)_{N_2} - h(T_0)_{N_2}\right] \quad (9)$$

$$E_{gas} = \left(V_{gas}/V_m\right) \sum_{i=1}^{5} [i]_{gas} \left(LHV_i + [h(T)_i - h(T_0)_i]\right) \quad (10)$$

Where, t_{h_b} and t_{ash} are respectively, the humidity and the ash content of biomass as given in the proximate analysis of biomass. c_{p_b}, $c_{p_{water}}$ and $c_{p_{ash}}$ are respectively, the specific heat of the biomass, liquid water and ash. n_{O_2} and n_{N_2} are the number of moles of oxygen and nitrogen contained in the air. The values of 1.5 and 0.84 $kJ.kg^{-1}K^{-1}$ were considered for c_{p_b} and $c_{p_{ash}}$, respectively (Roy et al., 2010; Ragland et al., 1991).

The energy lost in the ash and the unconverted carbon was estimated based on the mass and the ash content of the biomass, and the mass of residues obtained after the gasification as given by Equation 11. The sensible and chemical energies (given by LHV) were considered for biomass and gas energy calculation. The sensible energy of the gases species and the carbon (graphite) were computed by the enthalpy difference (Equation 12). The enthalpy values, $h(T)_i$, were taken from JANAF thermodynamic Tables (Chase et al., 1982).

$$E_r = (m_r - m_b t_{ash})(LHV_{carbon} + [h(T)_{carbon} - h(T_0)_{carbon}]) + m_b t_{ash} c_{p_{ash}} \left(T_{gas} - T_0\right) \quad (11)$$

$$E_{s_i} = h(T)_i - h(T_0)_i \quad (12)$$

The energy loss through the walls of the reactor can be estimated by the sum of the energy losses by convection and radiation according to Equation 13. ε, h_{cv}, A, T_{wall}, σ, T_{sky} and h are the emissivity of steel, the convection heat transfer coefficient, the area of reactor lateral outer wall, the mean temperature of the wall, the Stephan Boltzmann constant, the sky temperature and height of the reactor. The emissivity of steel of 0.39 was considered (Perry et al., 1997). T_{sky} was estimated from the ambient temperature on the basis of the correlation given by Equation 14 (Duffie and Beckman, 1980). According to Holman (2002), for a cylindrical reactor with a height h, h_{cv} was given by Equation 15.

$$E_{wall} = h_{cv} A\left(T_{wall} - T_a\right) + A\varepsilon\sigma\left(T_{wall}^4 - T_{sky}^4\right) \quad (13)$$

$$T_{sky} = 0{,}0552\ (T_a)^{1{,}5} \quad (14)$$

$$h_{cv} = 1{,}42\left(\frac{T_{wall} - T_a}{h}\right)^{0{,}25} \quad (15)$$

The energy gap (E_{gap}) was given by the difference of the incoming and outgoing energies as given by Equation 16.

$$E_{gap} = E_b + E_{air} - E_{gas} - E_r - E_{wall} \quad (16)$$

Gas sampling and analysis

The objective of the gas sampling is to determine the tar content in the gas, thus the isokinetic sampling is not necessary. The gas sampling line was checked and a vacuum leak test was conducted before the beginning of the gasification trials. The gas sampling for the determination of its gravimetric tar content and its composition was done approximately 10 min after the end of the biomass filling in the reactor when the high temperature is superior to 600°C in the reactor. The flame observation (at the flare) was used to estimate the gasification reaction establishment after the loading of the biomass in the reactor. Tars were sampled during the three trials. The dry gas is regularly introduced in a kynar gas sampling bag of 3 L. An Agilent 490 mico-GC equipped with two colons with flame ionization detector (FID) and katharometer detector was used for off-line dry gas analysis. The different gas analysed were CO, H_2, CH_4, CO_2, N_2 and O_2. The solution of isopropanol and tar are collected and then it evaporated in order to separate water and solvent (isopropanol) with the tar. The Laborota 4003 Heidolphrotavapor was used to evaporate the solution of isopropanol at 55°C.

RESULTS AND DISCUSSION

The impact of the pre-treatment of CS on the temperature fields was first analysed in this section. The temperature fields were used to calculate the mean temperatures along the reactor and then to localize the different reaction zones in the reactor. Secondly, the performances of the gasification of raw, torrefied and carbonized CS was analysed by using the mass and the energy balances. At the end, the gasification performances were

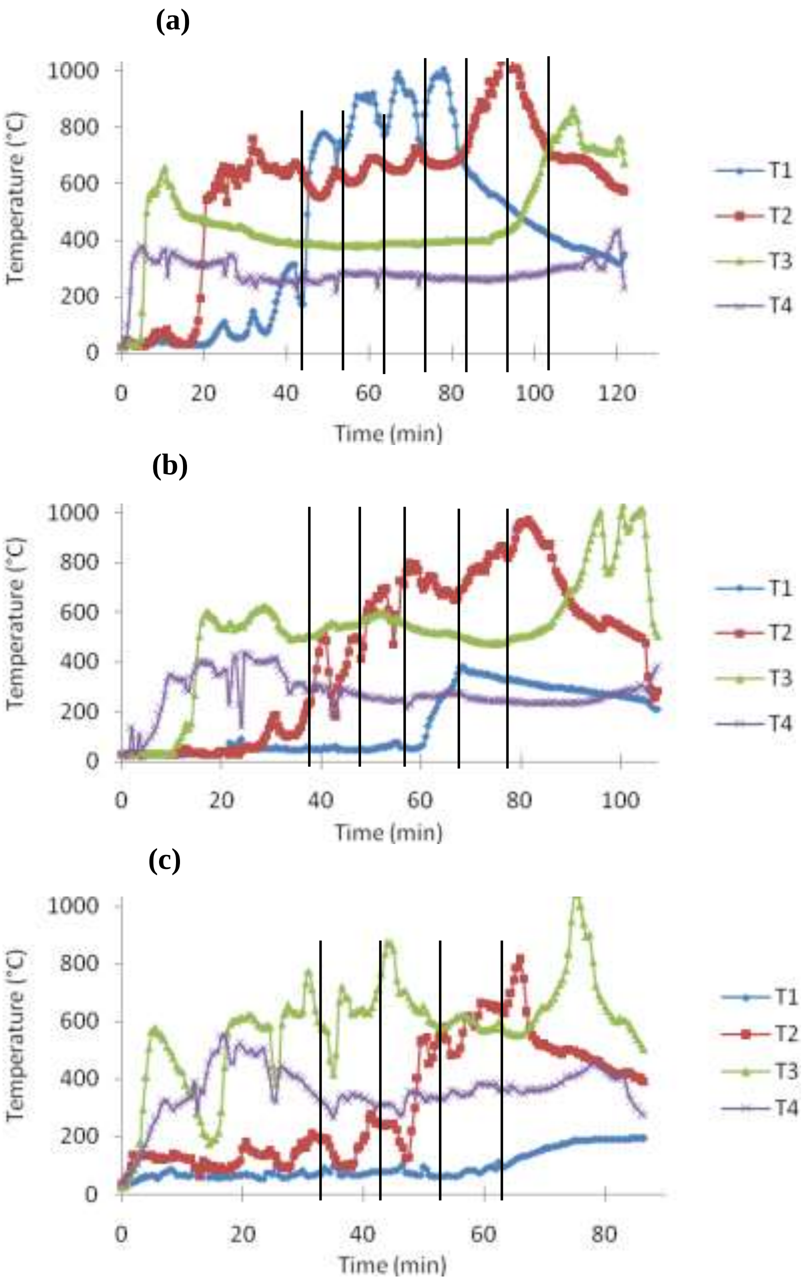

Figure 3. Temperature variation depending on the process, (a): Carbonized CS gasification, (b): Torrefied CS gasification, (c): Raw CS gasification. It should be noted that vertical lines indicate the time of the reactor feeding with biomass fuel and only four of the six measured temperatures were shown to avoid overload. T_1, T_2, T_3 and T_4 represent respectively, the temperatures at the top, middle, and bottom of the reactor and the temperature of the gas.

analysed by considering the gas tar content and the gasification energy efficiency.

Impact of pre-treatment on temperature fields and profiles

The temperature fields according to the CS nature (carbonized, raw and torrefied) was firstly described and then the results was analysed at the end of this section. Figure 3 presents the temperature variations in the reactor during the gasification of carbonized, torrefied and raw CS. The temperatures increased each time the biomass was introduced. T_4 is the first temperature which increased after the inflammation of the first part of biomass during the gasification of carbonized CS. Then

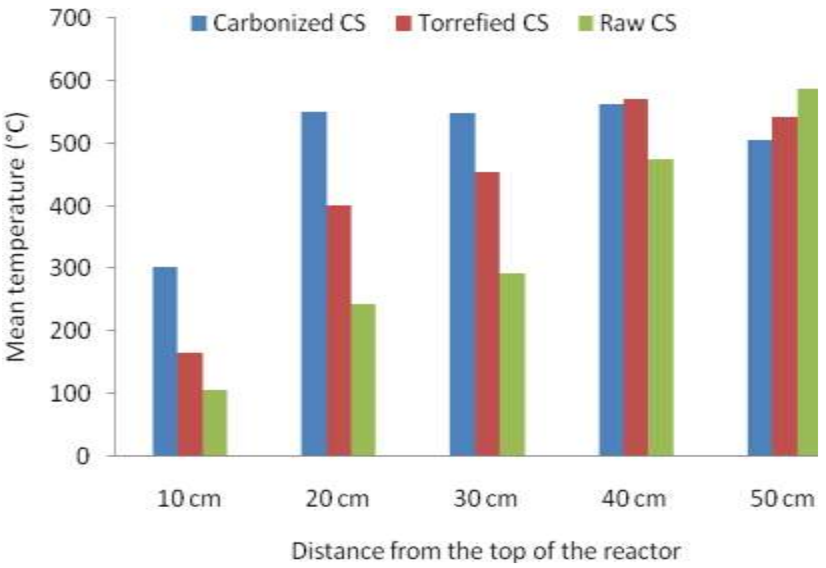

Figure 4. Mean temperatures measured at different distances from the top of the reactor.

T_3, T_2 and T_1 grew successively as the level of the fuel bed increased with the progressive loading of the biomass. The opening and filling of the reactor led to a sudden temperature drop across the combustible bed. The semi-continuous supply of biomass increased the level of the fuel bed and the temperature increased from the bottom to the top in the reactor. The reactor feeding generated the temperatures fluctuations mainly at the top of the reactor (T_1 and T_2). T_3 and T_4 were more stable during the reactor feeding. After the last loading of the biomass at t = 70 min, the decrease in the biomass bed level caused successive increase and decrease of the temperature along the reactor from the top to the bottom. The drop of T_3 means that most of the loaded biomass has been consumed and that the gasification is finished.

The temperature variations obtained for the torrefied and the raw CS gasification were similar to those obtained for the carbonized CS gasification. However, the temperatures obtained during the gasification of torrefied and raw CS are lower than those obtained during the gasification of carbonized CS mainly at the reactor top (T_1 and T_2). This is confirmed by the means temperatures obtained from the top to the bottom of the reactor during the gasification of raw, torrefied and carbonized CS, as shown in Figure 4.

The mean temperature at the reactor top and in the middle (10 to 30 cm) increased with the pre-treatment of CS. The highest mean temperatures at the reactor top and middle were achieved during the gasification of carbonized CS. At the reactor bottom, the mean temperature for the gasification of raw CS was higher than for the gasification of pre-treated CS. The mean temperatures during the gasification of the raw CS were considerably low (below 300°C) except at the reactor bottom. The slow rise of these temperatures was due to the higher thermal inertia of the raw biomass as compared to torrefied and carbonized biomass. Indeed, the raw biomass had a higher thermal conductivity, heat capacity and density than the torrefied and carbonized biomass (Andreas et al., 2013; Basu, 2013; Antal and Gronli, 2003). Therefore, the positions of the tree main zones of the gasification (pyrolysis, oxidation and reduction) along the reactor were affected by the pre-treatment of the biomass. The oxidation or combustion zone is located around the hottest part of the reactor and the pyrolysis and the reduction zones are located above and below the oxidation zone, respectively. The temperature profiles along the reactor were represented in order to locate the pyrolysis, the oxidation and the reduction zones during the gasification of raw and pre-treated CS (Figure 5). The temperature profile is defined as the temperature distribution along the height of the reactor at a given time. The temperature profile allows the identification of the different zones where each step of the gasification develops (pyrolysis, oxidation and reduction). Temperatures were taken every 10 min after the end of the biomass loading. The temperatures were generally below 1000°C.

The temperature profiles indicated that the oxidation zone has moved from the top to the bottom of the reactor during the gasification of the carbonized CS. The oxidation zone was located practically at the top of the biomass bed. After each filling of the carbonized CS, the drying and the pyrolysis proceeded rapidly with contact between the oxidation zone (at the top) and the newly introduced carbonized CS. Therefore, the drying zone and the pyrolysis had a very limited thickness. This is due to the low water and volatile matter content of the

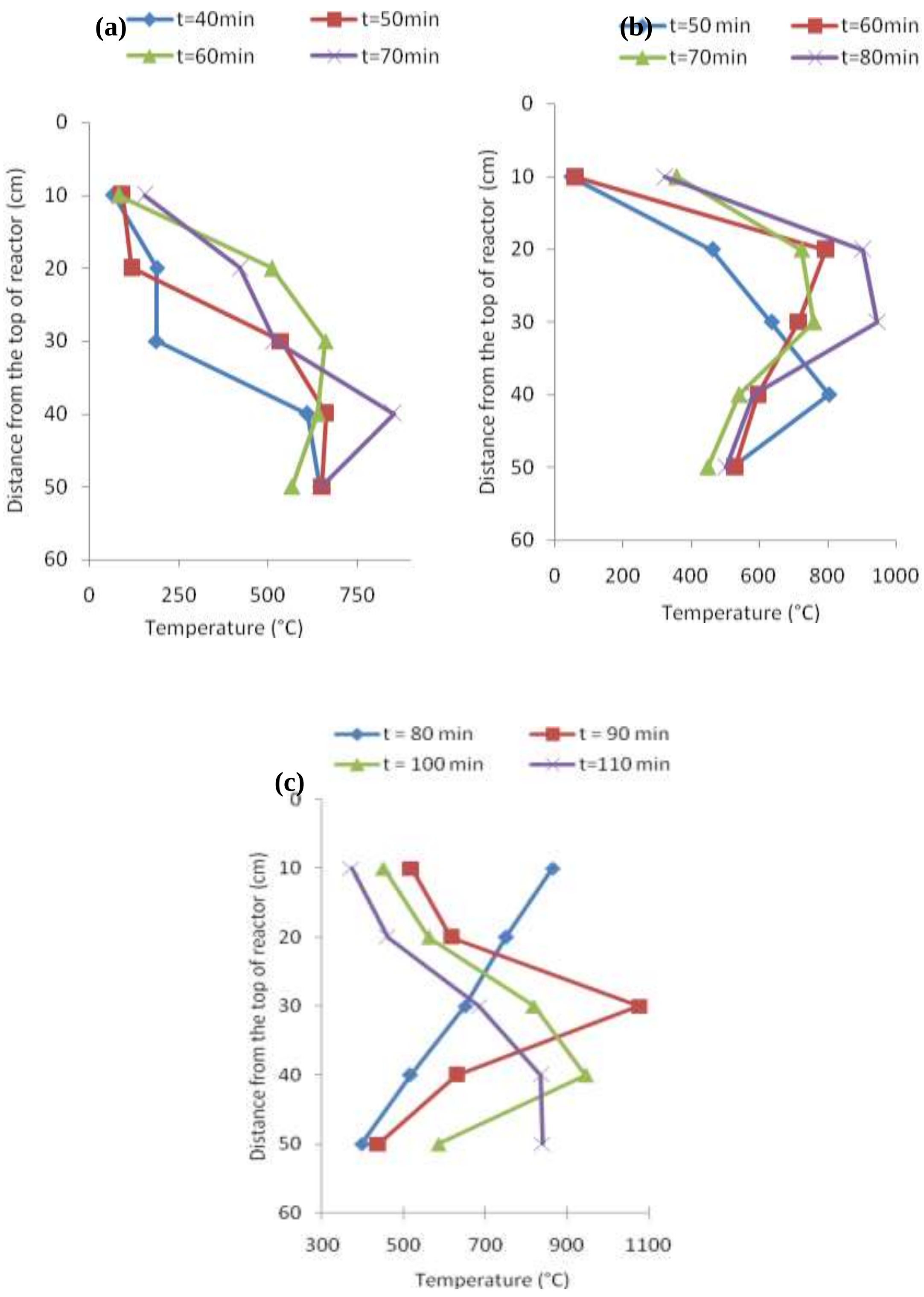

Figure 5. Temperature profiles depending on the process. (a): Raw CS gasification, (b): Torrefied CS gasification, (c): Carbonized CS gasification.

carbonized CS. In addition, the low thermal inertia of the coal favoured the heat transfer towards the top of the reactor; this facilitates the heating of newly introduced carbonized CS. Similar trends were obtained in the gasification of charcoal (Van de Steene et al., 2010).

The oxidation and reduction zones were basically

Table 2. Mass and energy balance for gasification of raw, torrefied and carbonized CS.

Biomass type	Mass balance (kg)					Energy balance (MJ)						
	m_b	m_{air}	m_r	m_{gas}	Δm	E_b	E_{air}	E_{gas}	E_{ash}	E_{carbon}	E_{wall}	E_{gap}
Raw CS	6.8	13.4	1.1	17.8	1.3	103.40	0.05	60.68	0.08	24.42	9.61	8.66
Torrefied CS	6.8	15.7	1.8	17.6	3.1	117.63	0.02	45.15	0.09	45.04	16.86	10.51
Carbonized CS	6.3	27.8	1.5	29.3	3.3	156.33	0.03	72.74	0.11	32.07	39.65	11.79

located at the reactor bottom for the gasification of raw CS. Indeed, the reactor mean temperature at the top was lower than 200°C during the gasification of raw CS. Therefore, the CS located in this part of the reactor was just dried. The appearance of the drying zone was due to the high moisture of raw CS comparatively to carbonized CS. The temperature in the middle of the reactor was also low during gasification. It was generally below 600°C. Therefore, pyrolysis occurred in this zone. The oxidation reaction can be developed in this zone due to the presence of oxygen. This zone is called the pyro-oxidation or the flaming-pyrolysis zone. Pyro-oxidation began at a temperature of 200°C after the biomass drying step. The end of the pyro-oxidation zone coincides with the consumption of available oxygen. The reduction reaction was developed at the reactor bottom. Thereafter, the boundary between the pyro-oxidation zone and reduction was stabilized at 20 cm above the grid.

An intermediate configuration between the temperature profiles of carbonized and raw CS was obtained for the gasification of torrefied CS. Indeed, the highest temperatures were located in the middle of the reactor (750-950°C). The boundary between the pyro-oxidation zone and the reduction zone is located in the middle of the reactor. The pre-treatment has caused the displacement of the oxidation zone upward the reactor. The reduction zone is thicker than for raw biomass gasification. Thus, the thermal and catalytic cracking of the tars may be more pronounced for the gasification of pre-treated biomass particularly for the carbonized biomass.

Mass and energy balances

The mass and energy balances are summarized in Table 2. Mass balances can hardly be completed since there are measurement uncertainties and some constituents such as the water vapour contained in the gas cannot be accounted for as stated in many studies (Jayah et al., 2003; Dogru et al., 2002).

The mass differences (Δm) between the mass of the reactants and the mass of the products can achieve 10% of the reactants mass during the gasification trials (Jayah et al., 2003; Dogru et al., 2002). In the present study, Δm of 6.4, 9.7 and 13.7% were obtained respectively for the raw, carbonized and torrefied CS gasification. The high percentages of the mass differences were due particularly to the measurement uncertainties and the mass of the water vapour contained in the gas which was not measured. It is noteworthy that the mass of water vapour can achieve 3% of the reactants mass (Martinez et al., 2011). In addition, the fine particles were not accounted for and were included in the mass differences. These fine particles had been observed after the gasification trial in the sawdust filter as shown by Figure 6a.

The major concern in the mass and energy balances was the high mass of residues which was significant as compared to the mass of the filled combustible for the three types of biomass. The ratio of the mass of residues and the mass of the introduced combustible was estimated to be 16, 24 and 26% for raw, carbonized and torrefied CS, respectively. The ratio of the mass of residues on the introduced mass of biomass varied from 1 to 10% in the literature (Martinez et al., 2011; Jayah et al., 2003; Dogru et al., 2002). The difference is probably due to the grate holes which allowed the ejection of unconverted carbon particularly during the grate stirring. The grate holes were square with a length of 0.5 cm as shown in Figure 6b. As a consequence, a complete conversion was not achieved during the gasification trials and the energy lost through the residues was considerable due essentially to the unconverted carbon. This energy lost in the residues was 20.7, 23.8 and 38.5% of the energy content of carbonized, raw and torrefied CS. The ratio of energy lost through the residues was particularly high during the gasification of torrefied CS. The low energy content and the high mass of the residues of torriefied CS gasification comparatively to carbonized and raw CS explained this difference. In addition, the low reactivity of the char from torrefied biomass could explain this fact. It was established that the char obtained from torrefied biomass are less reactive than those obtained from the raw biomass (Karlström et al., 2015; Fisher et al., 2012; Jones et al., 2012).

The energy loss through the evacuated hot ash was very low due to the small amount of ashes. The energy lost was also increased by the heat loss through the reactor walls particularly for the gasification of the carbonized CS during which it have represented 25.3% of the biomass energy content. Further efforts are needed to improve reactor insulation and biomass conversion especially the residence time in the reactor by the mean of a better ash evacuation system. The considerable

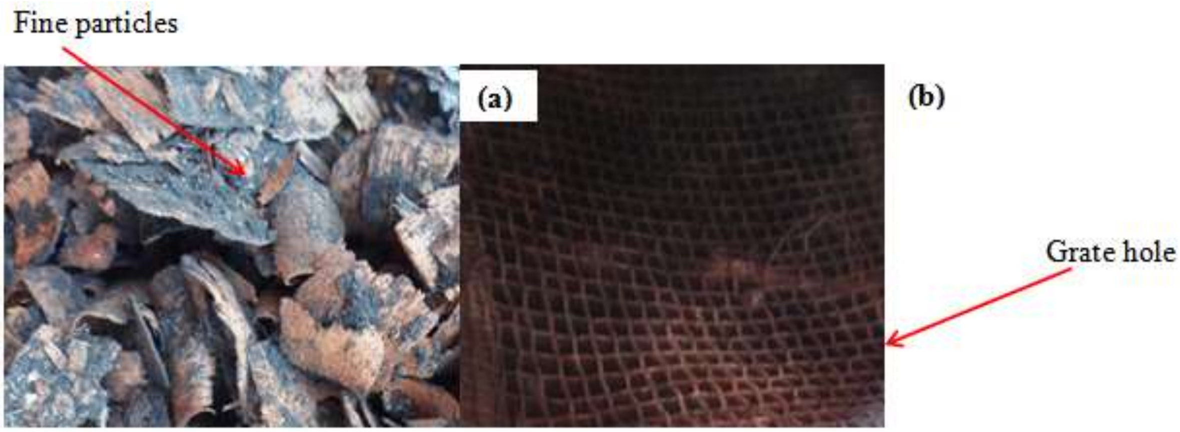

Figure 6. (a) Presence of fine particles at the top of sawdust filter after the gasification trials; (b) The grate holes which allowed the injection of unconverted carbon

mass of the residues, the heat lost through the walls led to a decrease of energy conversion efficiency.

Impact of pre-treatment on the tars content

The energy efficiency (η_{gas}) and the tar content of the gas were investigated for each type of biomass (raw, torrefied and carbonized CS) as shown in Table 3. The energy efficiency was determined by the ratio of the energy content in the volume of the gas to the energy content in biomass used (Equation 20).

$$\eta_{gaz} = E_{gas}/E_b \tag{20}$$

The energy efficiency have decreased for the gasification of torrefied and carbonized CS. In contrast, some authors have reported an increase in the gasification efficiency during the gasification of the torrefied biomass as compared to the raw biomass (Kuo et al., 2014; Prins et al., 2007). However, the gasification of the biomass torrefied in severe conditions, as it is the case for the torrefied CS used in the present study, has led to a decrease of energy efficiency as compared to the raw biomass (Kuo et al., 2014; Sarkar et al., 2014). In addition, the energy efficiency obtained for the gasification of torrefied CS were lower than those obtained for the gasification of carbonized CS. The low energy conversion observed for the gasification of torrefied CS was the basis of the low energy efficiency of gasification of pre-treated biomass by torrefaction. In the opposite trend, the cottons stalks pre-treatment reduced considerably the tar content of the gas.

Gasification of raw CS produces twice as much tar than torrefied CS gasification and 40 times more than the gasification with carbonized CS (Table 3). Other authors have found a reduction of 30% of tar concentration by the gasification of torrified wood comparatively to raw wood (Di Marcello et al., 2017). The low volatile matter content of the pre-treated CS and the high temperature achieved during the gasification of pre-treated biomass may be the causes of the tar content reduction. The volatile matter content was reduced from 76.60 to 68.50 and 24.15% for the torrefaction and carbonization of CS, respectively (Table 1). As the pre-treatment temperature increased (from torrefaction to carbonization), the volatile mater decreased and tar content dropped. The decrease of the tar content according to the severity of the torrefaction was also obtained in the literature during the gasification of torrefied waste at medium and severer condition (Recari et al., 2017). In addition to the volatiles reduction, the high temperature achieved (900 to 1000°C) and the thick reduction zone obtained during the pre-treated biomass gasification favoured the tar thermal and catalytic cracking as suggested by Dudyński et al. (2015). This had contributed to the reduction of the tar content even though the tar content of the gas depends also on the operating conditions and on the reactor design. Further research efforts are needed to understand the most important factor (between volatile matter reduction and temperature increase) affecting the tar content during the gasification of torrefied and carbonized biomass.

Table 3. Energetics performances and tar content of the gasification of raw, torrefied and carbonized CS.

Biomass type	η_{gas} (%)	Tar (g/Nm^3)
Raw CS	58.7	4.41
Torrefied CS	38.4	2.24
Carbonized CS	46.5	0.10

The tar content of the gas is the main competitiveness problem of the biomass gasification process. Therefore, despite the drastic loss of energy during gasification of carbonized CS, the process may be profitable for electricity production with pre-treated biomass using an internal combustion engine. The gas treatment cost can be greatly reduced when its tar content is low. In the case where CS is available at low cost, the process using the carbonized CS can be competitive, as compared to process using the raw CS due to the difference in costs related to the purification of gas. The use of torrefied CS can be seen as an intermediate solution. The producer gas of torrefied CS had reduced the energy losses and contains half less tar than the producer gas of the raw CS. A detailed economic study on the entire chain of the three processes, should determine the most viable process technically and economically.

Conclusion

Gasification of raw, torrefied and carbonized cotton stalks was studied in a small downdraft reactor and with air as gasification agent. High temperature and considerable energy lost was observed during the gasification of pre-treated biomass by torrefaction and carbonization. The energy lost was mainly due to the energy content of the gasification residues and the energy lost through the reactor walls since the temperature was high for the pre-treated CS. The results showed a decrease of energy efficiency during the gasification of torrefied and carbonized CS comparatively to the gasification of raw CS. Indeed, the energy efficiency of the gasification had decreased from 58.7% for the raw CS to 38.4 and 46.5% for torrefied CS and carbonized CS, respectively. However, the present study found an interesting decrease of the gas tar content according to the severity of the pre-treatment (from torrefaction to carbonization) due to the volatile matter decrease and the temperature increase. Tar content of 0.10 g/Nm^3 was obtained during the gasification of the carbonized cotton stalks against 4.2 g/Nm^3 for raw CS. More investigations may allow a better understanding of the impact of the severity of the pre-treatment on the gas tar content. It should be noted that the very low tar content achieved during the gasification of pre-treated CS, particularly the carbonized CS, make possible the development of the electricity production at low kWh cost, based on CS. Further efforts are needed in order to increase the carbon conversion and energy efficiency.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

Nomenclature: CS, Cotton stalks; V_N **,** normal volume (Nm^3); S_g **,** cross sectional area of the reactor (m^2); t**,** gasification time (min); LHV**,** low heating value (MJ.m^{-3} or MJ.kg^{-1}); m**,** mass (kg); T_0**,** normal temperature (273.15 K); T_a**,** ambient temperature (K); T**,** gas temperature (K); P_a**,** atmospheric pressure (1.013 bar); $\rho_{N_2}(T)$**,** density of nitrogen at temperature T (kg.m^{-3}); n**,** mole of the gas species (mol); M**,** molar mass of the gas species (g.mol^{-1}); V_m**,** molar volume (m^3.mol^{-1}); $[i]$**,** mole fraction of the gas species i (mol.mol^{-1}); **A,** exterior lateral surface of the reactor (m^2); ε**,** emissivity of the reactor walls; **Σ,** Stefan-Boltzmann constant (5,675.10^{-8}.W.m^{-2}.K); T_{wall}**,** temperature of the reactor walls (K); c_p**,** specific heat (kJ.kg^{-1}K^{-1}); C_p**,** molar specific heat (kJ.mol^{-1}K^{-1}); t_h **,** humidity content (%); t_{ash} **,** ash content of the biomass (%); h**,** height of the gasification reactor (m); $h(T)$**,** molar enthalpy at temperature T (kJ.mol^{-1}); E**,** energy content (MJ); i**,** gas species i, (CO, CO_2, H_2, CH_4, N_2); b**,** biomass type (raw, torrefied or carbonized cotton stalks); r**,** residues; $water$**,** liquid water.

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