Experimental investigation of hot water cogeneration using a carbonizer fit out with a preheating system

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Abstract

Carbonization is a thermochemical process that generates thermal energy and charcoal. The system allowing to recover the heat energy for co-, tri- and multi-generation is currently more investigated. The use of multi-generation systems is beneficial from the standpoint of increasing the usage of biomass, energy efficiency and reducing the impact on forests. The aim of this article was to design a carbonizer fit out with a thermal insulation layer and use it for the carbonization of some local biomasses, namely wood chips and teak wood. A heat recovery system was then incorporated into the carbonizer to cogenerate hot water from the thermal energy induced by the carbonization process. The results obtained with the designed carbonizer were 20% and 26% in mass yield respectively for teck wood and wood chips. The system developed that heat recovery was able to generate 25 L/h hot water at 45°C and 50°C during the first and the last phases respectively for wood chips and teak wood carbonization. The introduction of the preheating system induced a significant rise of the water's temperature. The highest maximum value of the hot water temperature was 62°C obtained during the carbonization of both studied fuels.

Keywords: hot water; preheating; heat recovery; carbonization; wood chips

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1 INTRODUCTION

With the limited fossil energy resources and global warming challenges, biomass appears as a credible renewable carbon resource. It is more and more mobilized and valued as an alternative for solid, liquid or gaseous fuels production [1]. In the context of sustainable development, controlling global energy consumption becomes one of the major challenges. The constant rise in world energy demand and the environmental problems caused by the fossil resources consumption make the renewable energy sources remains essential [2]. The biomass sector appears as a promising perspective for clean and sustainable energy production [3]. Biomass direct combustion with coal is the most used method of conversion and provides the greatest potential for large-scale utilization of biomass energy [4, 5]. Other thermochemical conversion technologies such as gasification and pyrolysis are technically feasible and potentially efficient for power generation, compared with combustion [6]. However, these technologies lack maturity and reliability or are not economically viable for large-scale utilization [7, 8]. Biomass-based cogeneration systems have been studied over the years by many researchers as a means of waste disposal and energy recovery [9–13]. In biomass-powered applications, the most popular fuels are wood and waste from its processing, straw, plants from energy crops and agricultural products [14–16]. In rural and sub-Saharan region over 90% of the households use firewood and wood charcoal fuel to meet their energy requirement for cooking and water heating [17]. The available water heating systems are fired either on solar energy or electricity and are costly affair for rural people in developing counties. New biomass based technologies to mitigate global warming are being proposed and investigated in many countries. Among these new biomass based technologies, multi-generation processes, including tri-generation, can make important contributions due to their potential for high efficiencies as well as

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low operating costs and pollution emissions per energy output [18–20]. However, cogeneration represents a relatively simple, integrated energy system involving the use of waste heat. Direct combustion of biomass remains a good option for water heating in rural areas because it is easily available with affordable price. Water heating through the burning of biomass is accomplished by either direct combustion or gasification. Traditional method of direct combustion for water heating systems is characterized by incomplete combustion and poor heat transfer efficiency. Despite technological progress and biomass conversion performance, carbonization remains an efficient and less expensive means for the plant remains recovery. In addition, the systems allowing to recover and valuate the lost thermal energy produced during the carbonization process are not widely investigated.

The aim of this study was to design and develop a high yield biomass carbonizer equipped with the lost thermal energy recovery system to cogenerate hot water.

2 MATERIAL AND METHODS

The conversion of biomass to produce charcoal is an exothermic process that generates heat. The magnitude of the heat generated depends not only on the design of the carbonizer (where the biomass-to-charcoal conversion process takes place) but also on the nature of the initial biomass involved in the process. Using a suitable energy recovery system incorporated to the carbonizer could help to heat water, which can be used for many purposes.

2.1 Raw biomasses collection and preparation

The teck wood was collected from Lomé city and was used as control. Figure 1 presents photographs of different raw biomasses used in the present study. All the raw biomasses used were first sun-dried until a constant mass before being introduced in the carbonizer.

(a)

(b)

Figure 1. *Raw biomasses used: (a) teak wood and (b) wood chips.*

2.2 System components

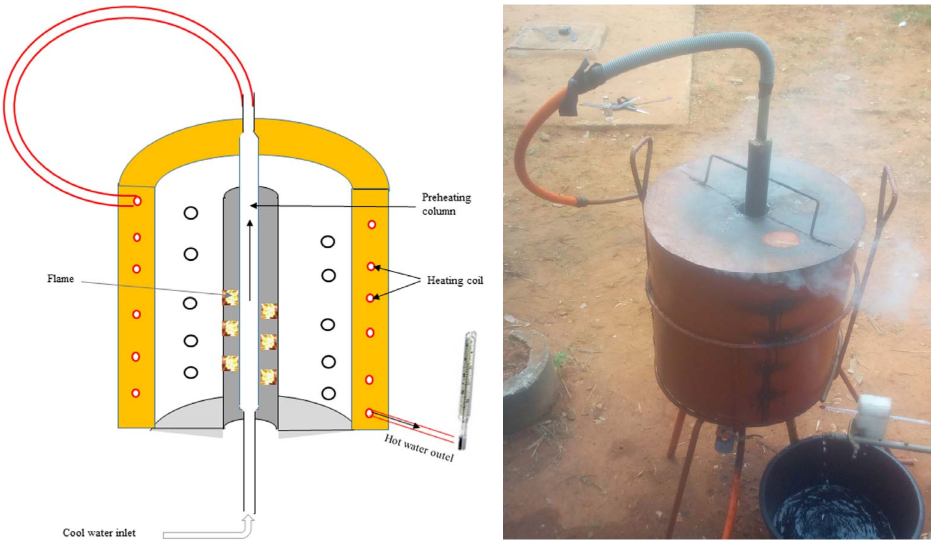
To evaluate the technical possibility of using a biomass carbonizer to generate hot water, a laboratory prototype carbonizer-heat recovery system was set up using the following components: the biomass carbonizer and heat recovery system (preheating and heating systems).

Figure 2 shows the schematic sectional and photograph of the used carbonizer equipped with a heat recovery system.

2.3 Biomass carbonizer

The carbonizer used in the present work is based on the partial combustion of biomass (Figure 2). It is composed of three coaxial cylinders. The inner cylinder or aeration column has a diameter of 8.26 cm, while the outer diameter is 40.21 cm, and between these two cylinders, there is another one with a diameter of 29.21 cm. The three cylinders are 40.00-cm high. The bottom of the outer cylinder is closed by a cover pierced with a hole of diameter equal to the diameter of the inner cylinder. The side of each cylinder is pierced with 16 holes through which the pyrolysis gases from the combustion chamber enter the aeration column during carbonization process. The inner cylinder is open right through. A flat cover with a hole whose diameter is equal to that of the inner cylinder covers the carbonizer (Figure 2b). From this top opening, the residual pyrolysis and combustion gases escape. The carbonizer is filled with an average mass of 3500 g for wood chips and 6000 g for teck wood. The carbonization chamber shell was insulated by interposing clay layer to prevent heat loss. In addition, the pyrolysis gas produced inside the carbonization chamber was partially burned in the column before coming out. This phenomenon contributes to further raising the temperature of the water.

The introduction of the biomass inside the carbonizer was done in two stages. The first part of the biomass was charged and then ignited (Figure 3a). As soon as the combustion started well, the



(a) (b)

Figure 2. *(a) Schematic representation of the section and (b) the photograph of the carbonizer.*

(a) (b)

Figure 3. *Ignition of the charge (a) and filled carbonizer (b).*

carbonizer was filled with the rest of the biomass. The height of the load was lower than that of the inner cylinder to ensure better closure and uniform carbonization (Figure 3b).

The hot water production component is composed of two parts: the preheating column and the heating coil.

2.4 Heat recovery system

On the carbonizer used in this work, heat is mainly lost on the side faces and through the inner column where the pyrolysis gases were burned. Thus, heat recovery components have been introduced at these two places. A copper coil acting as the heating system has been wound around the carbonization chamber and in the heart of the clay layer that partially prevents the sides' from heat loss. A stainless steel column introduced into the gas combustion chimney acts as the preheating system and makes it possible to recover part of the lost heat (Figure 2a).

2.5 Biomass charcoal yield and residence time

2.5.1 *Biomass charcoal yield*

The biomass charcoal yield (BY) was determined as the ratio of the biomass charcoal mass produced (m_2) to the sun dried raw biomass mass (m_1) subjected to carbonization as shown in Equation (1):

$$BY = \left({}^{m_2}\!/_{m_1} \right) * 100 \qquad (1)$$

The average yield was calculated as the average value of BY.

2.5.2 *Residence time*

The residence time (RT) is the time for which the biomass was subjected to high temperature in an oxygen-poor environment. In the present work, RT corresponds to the duration of the carbonization process.

3 RESULTS AND DISCUSSION

The raw biomass is fed into the carbonizer at half full and ignited by a flame using kerosene (Figure 3). When the combustion took place, the carbonizer was completely filled. Partial combustion took place at the ignited region of the carbonizer. Limited amount

Table 1. *RT and average yield of carbonization.*

Biomass type	RT (min)	Average yield (%)
Wood chips	130	26.28
Teck wood	180	20.30

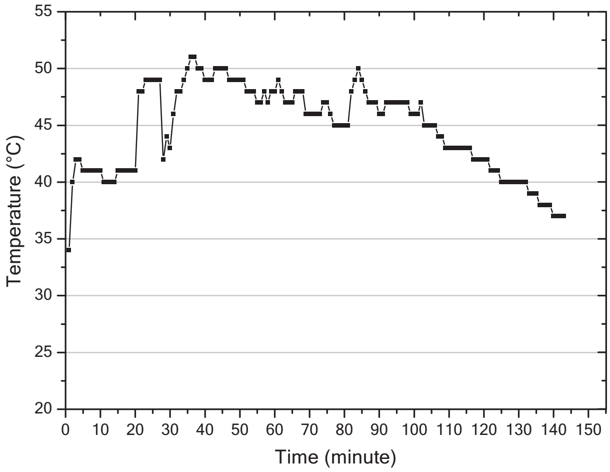


Figure 4. *Hot water temperature variation with time using heating system with wood chips biomass.*

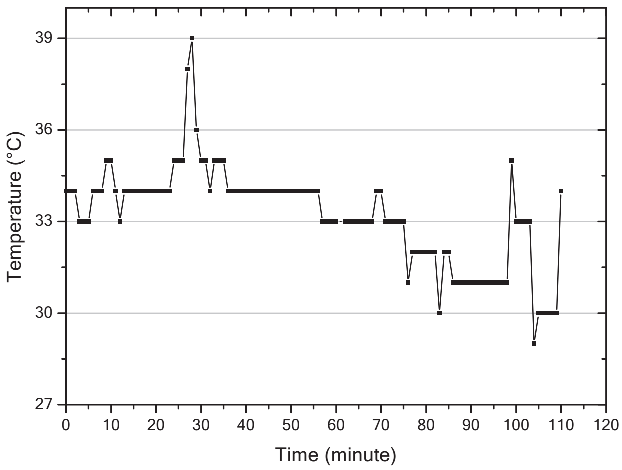


Figure 5. *Hot water temperature variation with time using preheating system with wood chips biomass.*

of air enters into this region through the side opened side, passing through the biomass. The carbon reacts with the oxygen of to produce carbon monoxide (CO). Other chemical reactions took place in a similar manner as that of gasification [21] resulting in the production of other combustible gases such as hydrogen (H_2) and methane (CH_4) gas. These combustible gases enter into the combustion chamber where they are combusted after mixing with the ambient air passing through the lower carbonizer opening [22].

Table 1 presents the RT and the BY obtained during the thermal carbonization of the two raw biomasses studied in the present work.

During the carbonization, an average yield of 20.30% and 26.28% were reported respectively for teck wood and wood chips. The average yield reported for wood chips was better than that of teck wood used as reference. The better average charcoal yield obtained for less dense raw material (wood chips) could indicate that the carbonizer developed in this work is more suitable for biomasses.

At the beginning of this study, a heating system constituted of a copper coil and the preheating column was used separately for heat recovery. Both components were then used simultaneously for heat recovery. During the present study, the cool water's temperature remained almost constant and ranged from 30°C to 32°C. Figure 4 presents the hot water temperature variation during the carbonization of wood chips with the heating coil used alone for energy recovery. When the carbonization process begins properly, the water temperature increases until reaching a maximum value of 51°C during the first 36 minutes. After this time, the water temperature decreases until reaching a minimum value (37°C). Period during which the obtained hot water temperature was greater than 45°C was ~85 minutes. In this study, constant hot water flow rate of 25 L/h was applied.

The variations of the hot water temperature when the preheating system was used alone for heat recovery are shown in Figure 5. As soon as the carbonization process begins properly, the temperature of the hot water produced increases with time until it reaches a maximum value and decreases. During the first 29 minutes, the water temperature increases slowly until reaching a maximum value of 39°C and after this period the temperature decreases. Time when the obtained hot water temperature was greater than 33°C was ~75 minutes.

The maximum temperature reached in the case of preheating system is lower than that of heating system. This could be explained by the geometry difference between the two systems. In fact, the coil length and diameter are 10 m and 1.2 cm, respectively, while the preheating column is only 40-cm long and three times larger.

Figure 6 presents the hot water temperature variation when the preheating and heating components were used together for heat recovery.

For this double configuration, the temperature increases over time until it reaches a maximum value of 62°C and then decreases. From this moment, the temperature undergoes decreasing fluctuations until reaching the minimum temperature of 41°C. However, the maximum and minimum temperatures obtained are higher than those obtained for the column and coil configurations alone. The highest hot water temperature was reported during the first phase of carbonization. Times when the obtained hot water temperature was greater than 45°C and 50°C were respectively about 90 and 45 minutes.

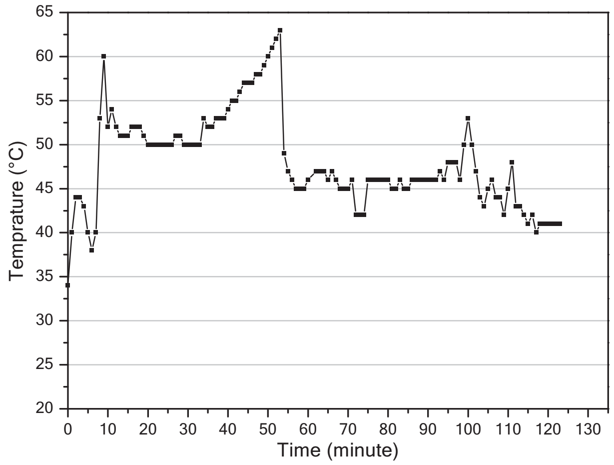


Figure 6. *Hot water temperature variation with time using preheating-heating system with wood chips biomass.*

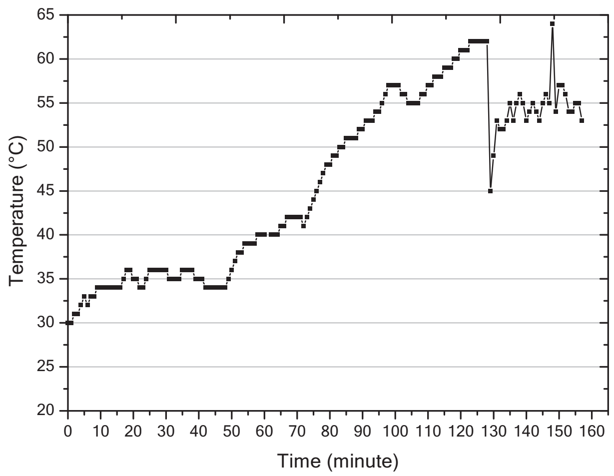


Figure 7. *Hot water temperature variation with time using preheating-heating system with teck wood.*

Figure 7 shows the temperature change of the hot water produced as a function of time for the double column-coil configuration during the carbonization of teak wood. When the carbonization process begins properly, the temperature of the hot water increases over time until it reaches a maximum value and then decreases.

During the first 128 minutes, the water temperature increases considerably until it reaches the maximum temperature of 62°C. After this period, the temperature undergoes decreasing fluctuations until reaching a minimum temperature (53°C). The hot water's temperature profiles observed in the present study were similar to those obtained by Sanjay *et al.* [23]. However, the best stability of hot water temperature they obtained could be due to the difference in the heat recovery system and the combustion process instead of carbonization. The highest hot water temperature was observed in the second phase of carbonization. Times when the obtained hot water temperature was greater than 45°C and 50°C were respectively about 75 and 65 minutes. The high hot water production zone could result from the nature and density of raw biomass involved in the carbonization process.

4 CONCLUSION

The aim of the present study was to design a carbonizer equipped with a heat recovery system to cogenerate hot water from the thermal energy induced by the carbonization process. The results obtained during the carbonization process gave for wood chips an average yield of 26.28% higher than that of teak wood (20.30%). The designed carbonizer was more suitable for biomass.

The cogeneration of heated water has been done with two heat recovery configurations. Initially with the heating coil, an average temperature of 45°C was recorded for the cogenerated hot water during 85 minutes. In a second step, with the preheating column only used for energy recovery, an average temperature of 33°C was reported for hot water during 75 minutes.

The combination of the two-preheating column-heating coil configurations yielded best results. With the wood chips used as energy source, an average hot water temperature of 45°C and 50°C were recorded respectively during the whole and in the first phase of the carbonization process. An average temperature of 50°C for the obtained hot water was reported in the last phase during the carbonization of teak wood. A maximum temperature of 62°C of hot water was reported for the two biomasses sources involved in the present study.

The developed carbonizer and the heat recovery system delivered hot water at an average temperature of 45°C–50°C at a constant rate of 25 L/h. The results show that the developed system was technically efficient for hot water cogeneration. However, a suitable combination of the two raw energy sources could allow the constructed carbonizer and the energy recovery system to cogenerate hot water probably during the whole carbonization process at 50°C or more.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

SUPPLEMENTARY DATA

Supplementary material is available at *International Journal of Low Carbon Technologies* online.

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