

Full Length Research Paper

Design, realization of a fixed bed downdraft gasifier and conduction of preliminary gasification tests with balanites aegyptiaca hulls, rice husk and charcoal

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This work is focused on the design and testing of a co-current fixed bed gasifier with two air injections. The electric power of the gasifier was set at 10 kW. The design is based on experimental data relating to specific gas production rate, engine power efficiencies, biomass flow rate, pyrolysis and reduction time etc. The gasification tests were conducted with rice husk, hulls of balanites aegyptiaca and charcoal. The realized gasifier has a diameter of the grid and a total height of 14 and 87 cm, respectively. A mass of 6.7, 17.9 and 10.8 kg were respectively gasified for rice husk, hulls of balanites aegyptiaca and charcoal. The highest temperatures (968°C in the oxidation zone) were obtained during charcoal gasification with a reaction time of 244 min. the temperature of 625°C in the oxidation zone and a reaction time of 114 min were obtained for the gasification of the hulls of balanites.

Key words: Gasification, design, rice husk, balanites aegyptiaca hulls, charcoal.

INTRODUCTION

The socio-economic context of the African countries is characterized by a strong demography and low per capita income, particularly for the countries of the West African Economic and Monetary Union (UEMOA). The UEMOA countries must ensure a strong economic growth in order

to achieve a sustainable development of their populations. The achievement of such economic growth requires the increase of productivity particularly in the primary or even secondary sector. It is in this context that access to modern energy services such as electricity is

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essential because it helps to promote access to resources (water ...) necessary for the development of all sectors of the economy. Indeed, the rate of access to electricity in rural and urban areas of the UEMOA area is very low. In addition to weak economic growth, the lack of access to modern energy services such as electricity results in the predominance of traditional biomass which accounts for almost 80% of primary energy supply compared to 15% for hydrocarbons and only 5% for electricity (UEMOA, 2006). This is reflected by the deforestation aggravation, hence the need to find sustainable alternative sources and to modernize the biomass use as energy. Many efforts have to be made by African countries in this field. Indeed, biofuel generates 4% of electricity in Europe against the zero in Africa in 2017 (IEA, 2018). In such a context, the energy recovered from agriculture residues can make a significant contribution to improve the access to modern energy services. In addition to agricultural residues, forestry residues are recommended by Long et al. (2013) to increase the biomass potential to achieve a secure raw material supply for biomass energy conversion technology like gasification. Gasification is the production of a gaseous fuel from a solid fuel. The gas produced during the gasification can be used for heat and power production.

The development of this technology in the UEMOA zone requires on one hand a fully control of the techniques of design and realization of gasifiers and on the other hand an improvement of the performances of the process. The major difficulty related to the control of the process of gasification of biomass is related to the presence of tars in the gas. Indeed, the gas is generally produced with a high content of tar and dust. Gas treatment is needed before most applications, especially in an internal combustion engine. For these types of applications oriented towards electric and power production scrubbing and filtering of the gas are essentials to avoid embedding in the engine pipes. The additional cost of gas cleaning involves the increase of the production cost per kilowatt-hour (kWh) as well as the investment cost. The gasification technology still needs to be improved in order to compete in the energy market (Anjireddy and Sastry, 2011). It should be noted that the co-current type fixed-bed gasifier produces the least tar compared to other types of gasifiers, (Milne et al., 1998). This justifies the choice of this type of gasifier for the present study. It should also be noted that the design of a gasifier plays a crucial role in the efficiency of gasification, the gas heating value and the tars formation (Cao et al., 2006). For example, the injection of secondary air at the level of the biomass feed can lead to a reduction up to 88.7% in mass of total tars content (Pan et al., 1999); hence the importance of providing a secondary air supply on the gasifier. The objective of the work is to design, build and test a co-current type fixed bed gasifier equipped with a secondary air supply.

Agricultural and forestry residues such as rice husk and balanites aegyptiaca hulls were tested. The gasification of wood charcoal was also tested during the works.

MATERIALS AND METHODS

Design method

The gasifier is composed of a drying zone, a pyrolysis zone, oxidation zone and a reduction zone (Figure 1). A throat has also been provided in the oxidation zone to allow better thermal cracking of the tars. To dimension the Imbert gasifier, we can proceed as follows:

- (1) Set the nominal electrical power required (P_e) and the gasifying agent;
- (2) Choose the type of fuel (wood, rice husk, charcoal...), the gas lower heating value (LHV) and the efficiency of the electric conversion of the gas by the engine (τ_m);
- (3) Determine the appropriate parameters for sizing the gasifier using mathematical formulas, interpolation or experimental data.

The appropriate parameters for the design of the Imbert generator are: the throat diameter (d_{gr}) located above the reduction zone, the tuyeres diameter (d_r), the diameter of the charging zone (drying and pyrolysis) (d_c), the diameter of the nozzles (d_n), the height of the charging zone (H_c), the height of the inclination zone (H_i), the height of the reduction zone (H_r), the position of the tuyeres (h_{a1}), the inclination angle of the throat (α).

Choice of gasifier data

Choice of electric power and gasifying agent

The thermal power of the gasifier is of the order of 30 kW. This will meet the needs of low mechanical power (P_e) of the order of 10 kW. The use of air as a gasifying agent is inexpensive and the produced gas has a low LHV (varying between 3 and 5 MJ/Nm³) but sufficient for the electrical and thermal production. Thus, air was chosen as a gasifying agent for this study.

Choice of biomass, LHV of the gas and electrical efficiency of gasification

The gasifier is intended to be fed by a wide range of biomass, particularly agroforestry residues (rice husk and hulls of egyptiacabalanites). The HHV of the gas depends on the nature of the biomass used. A low HHV of the gas must be chosen for the gasifier sizing thus the targeted electrical power can be achieved even though the biomass produced gas has a very low calorific content. A gas HHV of 3 MJ/Nm³ was considered in this study. The electrical efficiency, which represents the ratio of the electric power to the thermal power of the biomass, depends on the performance of the device. Electrical efficiencies ranging from 25 to 27% have been reported in the literature (Henriksen et al., 2006, Mukunda et al., 1994). The electrical efficiency of 25% was considered in this study.

Determination of appropriate parameters

Gas flow

The determination of the gas flow d_g (m³/s) (Equation 1) makes it

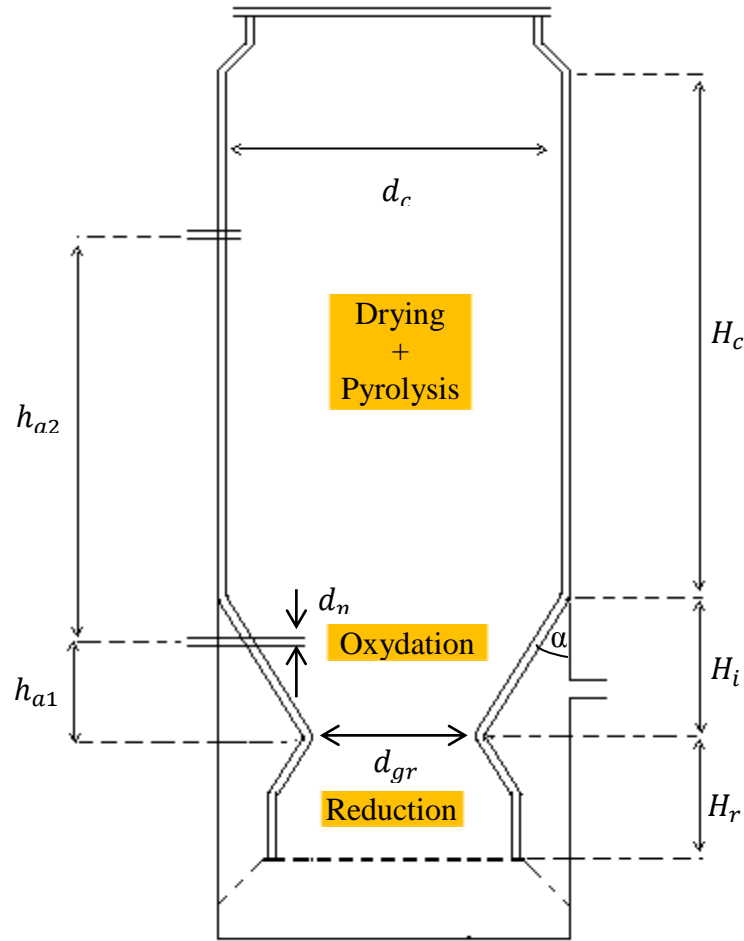


Figure 1. The different zones of the gasification and the basic dimensions of the gasifier.

possible to calculate the specific gas production rate, p_s .

$$d_g = P_e / r_m \times LHV_{gaz} \quad (1)$$

r_m : Engine efficiency; LHV_{gaz} : Lower heating value of the gas (3-5 MJ/Nm³).

Throat diameter

The throat diameter is determined from experimental data of the specific gas production rate. The specific production, p_s (m³.cm⁻².h⁻¹) and the throat surface are given by Equation 2. The throat diameter, d_{gr} (cm), is deduced from Equation 2 according to Equation 3.

$$p_s = 3600 d_g / S_{gr} \quad (2)$$

$$d_{gr} = 2 \sqrt{S_{gr} / \pi} \quad (3)$$

The throat load also called the specific gasification rate,

p_b (Equation 4), can be used instead of the specific production. p_b represents the fuel consumed per hour per cm² of the throat. The fuel mass can be estimated from the amount of the produced gas. Considering one kilogram of biomass produces around 2.4 to 2.5 m³ of gas, the fuel load per hour or the biomass consumption rate is given by Equation 5.

$$p_b = p_s / 2,4 \quad (4)$$

$$m_b = d_g / 2,4 \quad (5)$$

Tuyeres position and nozzles diameter

The position of the air tuyeres is obtained by the ratio, a_1 , between the position of the air inlets and the throat diameter in accordance with equation 6 (Swedish Academy of Engineering Sciences, 1979).

$$h_{a1} = a_1 d_{gr} \quad (6)$$

The diameter of the nozzles is also obtained based on the diameter of the grid (Swedish Academy of Engineering Sciences, 1979).

Diameter of the pyrolysis zone and the height of the inclination zone

The diameter of the pyrolysis zone is of the order of 4 to 2 times the diameter of the throat (Swedish Academy of Engineering Sciences, 1979). Thus for this study, the diameter of the pyrolysis zone, d_p , is 3.5 times the diameter of the throat (Equation 7).

$$d_c = 3.5 d_{gr} \quad (7)$$

The height of the inclination zone (H_i) is given as a function of the angle of inclination or throat angle (α) through the Equation 8:

$$H_i = \tan \alpha \times (d_c - d_{gr})/2 \quad (8)$$

The recommended value of angle α is in the range of 45° to 60° (Venselaar, 1982).

Height of the pyrolysis and reduction zone

The following simplifying assumptions can be made for determining the heights of the pyrolysis and reduction zone. The calculation of heights was based on the estimation of the fuel flow velocity and the time of pyrolysis and reduction (Reed and Levie, 1984). The flow velocity of the loaded combustible is given by equation 9 (Reed and Levie, 1984).

$$v_b = m_b / (S \times d_c \times \rho_{bulk}) \quad (9)$$

ρ_{vrac} the bulk density of the combustible load, S is the cross-sectional area of the pyrolysis zone. The pyrolysis time (equation 10) is determined by the ratio of the sum of the heat required for pyrolysis and the evaporation of water by the heat transfer flux of this zone (Reed and Levie, 1984).

$$t_p = \left((h_p + \tau_h \times h_e) \times V_p \times \rho_{bulk} \right) / (q \times S_p) \quad (10)$$

The terms h_p, h_e, τ_h, V_p, q and S_p respectively correspond to the heat required for the pyrolysis, the heat of the steam, the moisture content, the volume of the fuel particle, the heat transfer flux in this zone and the total lateral surface of the fuel particle. The time of charcoal reduction can be taken as 100 s regardless of the type of biomass (Reed and Levie, 1984). The heights of the pyrolysis and reduction zone will be given by Equations 11 and 12.

$$H_p = t_p \times v_b \quad (11)$$

$$H_r = t_r \times v_b \quad (12)$$

The height of the drying zone (Equation 13) located above the pyrolysis zone has been estimated to contain the hourly fuel load (m_b).

$$H_s = m_b / \rho_{bulk} \times S \quad (13)$$

The height of the charging zone (drying and pyrolysis zone) is given by the sum of the height of the pyrolysis zone and the drying zone

(Equation 14).

$$H_c = H_s + H_p$$

Gasification tests

Preliminary tests were carried out with the realized gasifier. Charcoal, rice husks and balanites hulls were used for the gasification tests (Figure 2). The biomass is weighed with an electronic balance of precision 5 g before filling progressively the gasifier. Four type K thermocouples were placed along the gas generator. A temperature recorder of the type Testo 176 T4 was used for temperature recording every 10 s. The process of gasification is done by introducing nearly one kilogram of biomass into the gasifier. Then about two hundred grams of charcoal are ignited and then introduced into the gasifier. Subsequently, the gasifier is filled and closed. Gas production begins once the flame ignites at the flare. The end of the gasification is indicated by the extinction of the flame and then the temperature drops at the gasifier bottom.

RESULTS AND DISCUSSION

The gasifier dimensions

The data used are summarized in Table 1. The typical value of the specific gas production rate (p_s) is 0.9 $m^3 \cdot cm^{-2} h^{-1}$ for an Imbert-type gasifier (Brandini, 1983). Thus the value of 0.9 $m^3 \cdot cm^{-2} h^{-1}$ was considered in this study. The height, h_{a2} , between the primary and secondary air tuyeres has been estimated so that the secondary air tuyeres will be placed at the fuel bed top. The dimensions considered for the gasifier realization are different from those estimated in order to take into account the technical capacity and the dimension of the available materials. The used values for the gasifier realization and theoretical estimated values are summarised in Table 2. The gasifier is shorter, but has a slightly larger reactive zone than the gasifier designed on the basis of calculations. The image of the gasifier is shown in Figure 3.

Results of gasification tests

The evolution of the temperature within the gasifier according to the time for each type of biomass used is given in Figure 4. Temperature rapid increase is observed during the gasification of agricultural residues (balanites hulls and rice husks) which is due to the rapid combustion at the primary air inlet at the beginning of the gasification trials. The temperatures dropped significantly after the reactor was closed during the gasification of raw agricultural residues. Thus, the oxidation front situated at the hottest point of the reactor stabilizes near the primary air inlet (at T_3) in the case of balanites hulls and charcoal. Gas production, which is indicated by gas ignition at the flare, occurs rapidly (less than 5 min after reactor closure) in the case of balanites hulls.



Figure 2. Biomass used for the gasification tests; (A) Charcoal, (B) *Balanites aegyptiaca* hulls, (C) rice husk.

Table 1. Data taken into account for the estimation of reactor dimensions.

Data	Values	Reference
Electric power (kW)	10	Estimation
Electricity efficiency	0.25	Estimation
LHV of the gas (MJ/Nm ³)	3.0	Estimation
$p_s(m^3 \cdot cm^{-2}h^{-1})$	0.9	Estimation
Biomass bulk density(kg/m ³)	300	Estimation
H _p (J/kg)	2081000	Reed et Levie, 1984
h _e (J/kg)	3654000	Reed et Levie, 1984
Moisture content (%)	20	Estimée
q (W/m ²)	20000	Reed et Levie, 1984
Biomass particle size (m)	0.02	Estimation
Throat angle (α)	55°	Estimation

Table 2. Estimated and used dimensions of the reactor.

Characteristics	Estimated dimensions	Dimensions of the realized gasifier
Volume flow rate of the gas, $d_g(m^3/h)$	40.0	-
Biomass consumption, $m_b(kg/h)$	16.7	-
Throat diameter, $d_{gr}(cm)$	7.5	14
Ratio, α_1	1.2	-
Tuyeres diameter, $d_r(mm)$	10	35
Position of the primary air tuyeres, $h_{a1}(cm)$	9	27
Position of the secondary air tuyeres, $h_{a2}(cm)$	100	50
Tuyeres number	5	3
Biomass flow velocity (cm/s)	0.11	-
Pyrolysis time (s)	131.5	-
Diameter of the pyrolysis zone, d_c (cm)	26.3	30
Height of the reduction zone, H_r (cm)	10.8	17
Height of the inclination zone, H_i (cm)	13.4	20
Height of the pyrolysis zone, H_p (cm)	14.1	-
Height of the drying zone, H_s (cm)	102.0	-
Height of the charging zone, H_c (cm)	116.1	50
Total height of the reactor (cm)	140.3	87

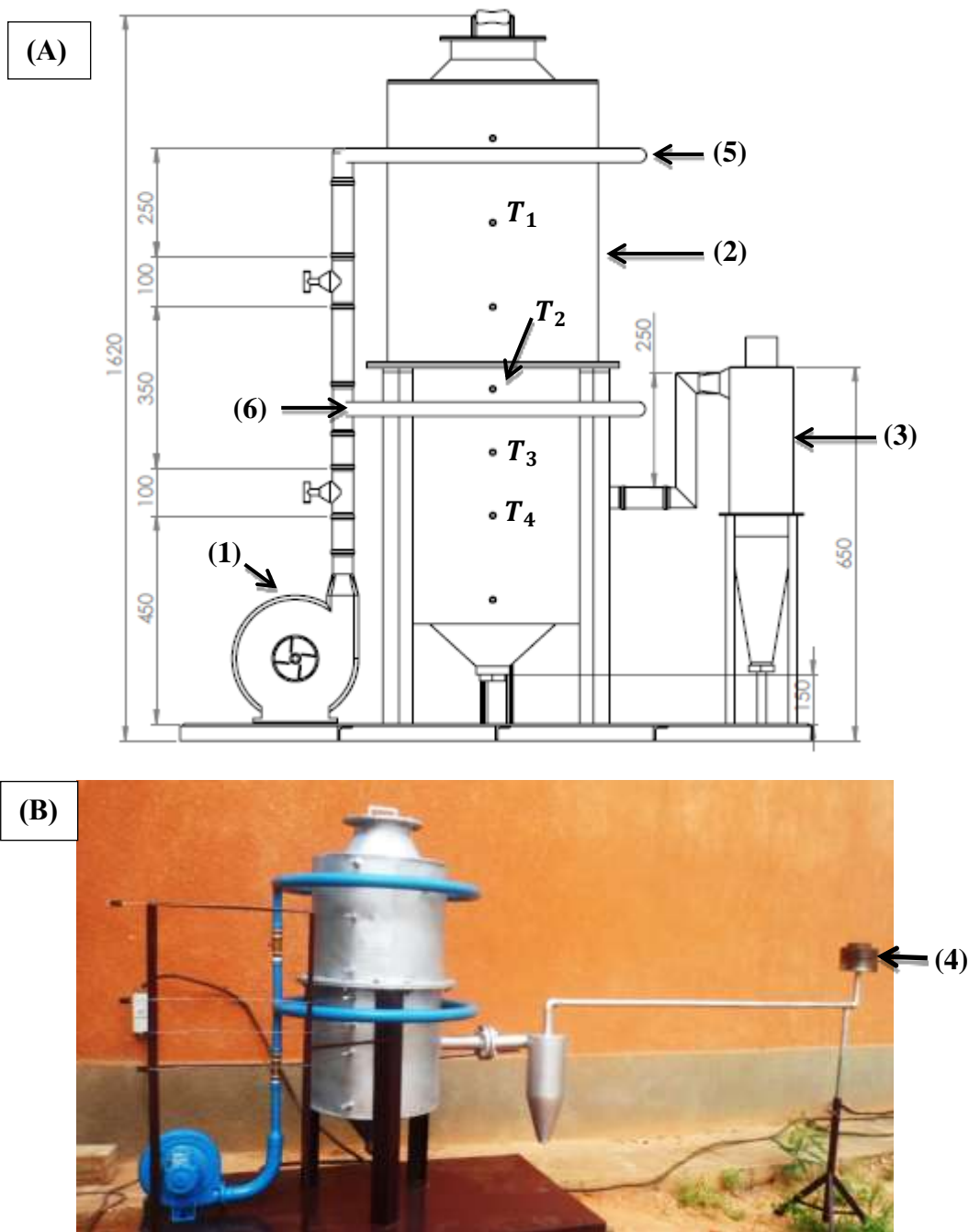


Figure 3. Schematic diagram (A), and Image of the gasifier (B). Position of the thermocouples and the different components of the device are represented: (1): Blower; (2): Reactor; (3) Cyclone; (4): Flare; (5): Secondary air tuyeres; (6): Primary air tuyeres.

Contrarily to the gasification of balanites hulls and charcoal, the front of the oxidation stabilized at the bottom of the reactor (at the level of T_4) during the gasification of the rice husk. Thus, the absence of a reduction zone at the bottom of the oxidation front has led to the absence of flame at the flare. A flowing problem of the rice husk inside the reactor was observed after the

gasification test. Indeed, the rice husk remains blocked in the upper part of the reactor (pyrolysis zone). Thus, the temperatures drop after burning the rice husk at the gasifier bottom. As a result, an agitator system is needed for future improvement of the gasifier. The biomass agitation system at the top of the reactor will force the rice husk to flow downward inside the gasifier.

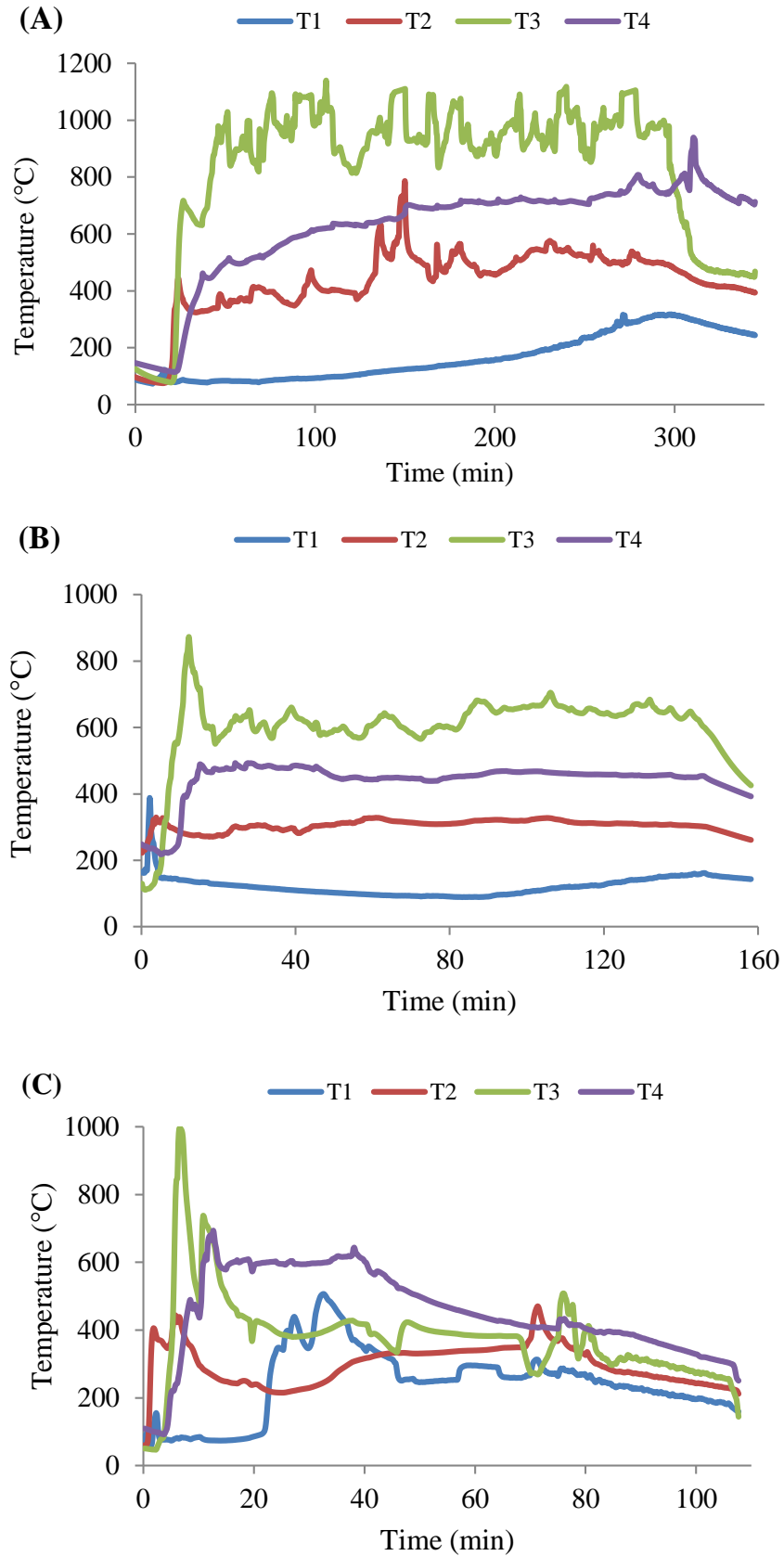


Figure 4. Temperatures in function of time during gasification tests, (A) case of charcoal; (B) case of balanites hulls; (C) case of the rice husk.

Table 3. Average temperatures, reaction durations and hourly and specific consumption during gasification tests.

Combustible type	Charcoal	Rice husk	Balanites hulls
T ₁ average in drying zone (°C)	154	282	109
T ₂ average in pyrolysis zone (°C)	473	291	309
T ₃ average in oxidation zone (°C)	968	408	625
T ₄ average in reduction zone(°C)	664	547	462
Consume combustible (kg)	10.8	6.7	17.9
Mass of the residues (kg)	1.9	-	1.8
Gasification duration (min)	244	54	114
Biomass consumption rate (m_b en kg/h)	2.2	4.8	7.2
Specific gasification rate ($\text{kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$)	143	313	438

The average temperatures, reaction durations, biomass consumptions and specific gasification rate obtained during the gasification trials were summarized in Table 3. The results show a high average temperatures and unconverted carbon (residues) and low biomass consumption rate obtained for charcoal gasification comparatively to the raw biomass gasification. Similar results were achieved by other authors (Harouna et al., 2018). The lower reactivity of charcoal comparatively to raw biomass is the principal cause of this fact. More investigations are needed to increase the combustible consumption by improving the air flow per example in order to increase the output power of the gasifier while it is mainly fuelled with charcoal. The injection of steam and air mixture may also help to improve the gasification process (He et al., 2012; Lv et al., 2004). This issue will be addressed during the future study for improving the gasification system designed and realized in the present work.

Furthermore, the biomass consumptions rate obtained are under the estimated consumption of 16.7 kg/h (Table 2). This explains the low specific consumptions obtained especially during the gasification of charcoals for which a specific consumption of $143 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ was obtained. Indeed, for this type of reactor a minimum specific consumption of $509 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ has been reported by Kaupp and Goss (1981). The low biomass consumption and the specific consumption is probably due to a low airflow, hence the need to review the blower power and the gasifier's air supply system by increasing the number of air inlets from 3 to 5 at least in the oxidation zone.

Conclusion

A co-current type fixed bed gasifier has been designed, constructed and tested in the present study. The mechanical power of 10 kW was targeted which led to an estimated biomass consumption of 16.7 kg/h and a throat diameter of 7.5 cm. The produced gasifier has a larger reactive zone than the gasifier designed with a throat

diameter of 14 cm. However, a low biomass consumption of 2.2, 4.8 and 7.2 was obtained during the gasification of charcoal, rice husks and balanites hulls respectively. This is due to a low air flow hence the need to increase the power of the blower and increase the number of air inlets from 3 to 5 at the oxidation zone of the gasifier. A flowing problem of biomass was observed after the gasification test of the rice husk. This did not allow the production of gas during the gasification of the rice husk hence the need to design and install an agitator system of biomass in the upper part of the gasifier.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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