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Experimental study of syngas generation from almond shell in a downdraft gasifier

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Abstract: An experimental study was carried out using a pilot scale throated downdraft gasifier to study the conversion of almond shell into a combustible gas. The experimental setup and the operating process were presented in details. During the experiments, temperature at the different zones of the gasifier was recorded using K type thermocouples. The product gas at the outlet of the reactor was analyzed and the fractions of the combustible gases were determined. The efficiency of the process was also evaluated based on the heating value of the solid fuel and the generated gas. The process could be considered as an interesting way to convert the energy stored in the solid fuel into a fuel gas more practical in its use.

Keywords: Almond shell, gasification, downdraft gasifier, product gas, energy efficiency.

1. Introduction

The sustainable green energies have the great potential to decrease the greenhouse gases emissions, reduce the dependence on the fossil fuels and satisfy the growing energy demand. Biomass, which includes forestry and agricultural residues, could be effectively used to provide several energy carriers. Indeed, the conversion of biomass feed-stocks into solid, liquid or gaseous fuels as well as heat and electricity could be achieved through several processes and techniques. The choice of the suitable conversion process is related to the properties of the feed and the intended application.

Among the biomass conversion technologies, gasification is considered as potential way for the production of gaseous fuel. Gasification is a partial oxidation process in which the biomass feed undergoes drying, pyrolysis, oxidation and reduction reactions to yield a gaseous mixture, containing hydrogen and carbon monoxide along with traces of hydrocarbons and other inert gases. A literature review shows that quite many researchers investigated biomass gasification using different reactors in both lab and pilot scales [1-11]. Several biomass feeds were also employed including woody species [3- 5, 8, 9, 11], agricultural residues (hazelnut shells [1, 6], groundnut shells [10], de-oiled cake [11]) and sewage sludge [7]. The goal is to study the feasibility of the biomass gasification and optimize the operating parameters for high quality syngas and/ or hydrogen production.

A simple and reliable reactor used in gasification is the downdraft gasifier. This reactor is commonly known for the production of a producer gas with low tar content. It is therefore more favored in the coupling to small scale combustion engines to generate heat and electricity. In an air blown downdraft gasifier, four distinct layers could be distinguished. Firstly, biomass feedstock loses its moisture in the drying zone; then it is subjected to pyrolysis leading to its decomposition into char and volatiles. These pyrolytic yields react with oxygen in the high temperature oxidation zone. Finally, the reduction reactions take place and yield product gas at the bottom of the reactor.
Two main configurations of the downdraft gasifier were investigated: the stratified and the throated downdraft gasifiers [8]. The first type is characterized by a cylindrical shape with a uniform cross section in all of the three sub-processes [9- 10], whereas the second type is characterized by the presence of a restriction on its cross section (known as throat) near the air inlet, i.e. in the oxidation zone [1- 8, 11]. The former configuration could significantly reduce the tar content in the producer gas by reducing the cold zones and by cracking and oxidizing most of the heavy compounds evolved in the pyrolysis zone.

In this work, almond shell gasification is studied in a pilot scale throated downdraft gasifier. The goal is to investigate the potential of gasification in the upgrading of a locally available biomass (almond shell) into a gaseous fuel. The efficiency of the process is assessed based on the heating value of the generated gas.

2. Experimental setup and procedure

2.1. Materials

The biomass feed used in the actual experimental study is the almond shell. This agricultural residue is quite suitable for gasification in a fixed bed since it is readily provided in small dried particles (bulk particle size around 1 cm) and it doesn't require any additional preparation. Table 1 shows the elemental analysis and the moisture content of the almond shell. Its high heating value (HHV) was approximated using correlation (1) [12]. A small amount of char wood (5 kg) was put in the reduction zone of the gasifier and distributed on the grate before the introduction of the almond shells at the beginning of the experiments [2, 10]. The goal is to heat up the gasifier quickly and reduce the pyrolysis gases emissions at the beginning of the run [2, 3].

$$HHV(kJ/kmol) = 0.2949.C + 0.825.H \tag{1}$$

Table 1: Elemental analysis of almond shells

Ultimate analysis (dry basis)	% mass
Carbon	45.64
Hydrogen	6.19
Oxygen	45.43
Nitrogen	<0.5
Ash	2.71
Moisture content	9.54
HHV *(MJ/Kg)*	18.56

2.2. Experimental Setup

Gasification experiments were carried out in a pilot scale fixed bed biomass downdraft gasifier. The pilot unit is schematically represented in figure 1. The downdraft biomass gasification unit is a batch type system. It comprises a throated reactor, a suction type air blower, a perforated grate, an ash collector and a producer gas cooling and sampling line. The reactor consists of a stainless steel cylinder with a total height of 1200 mm and an inner diameter of 800 mm. The throat was situated at 250 mm from the grate level and had a diameter of 200 mm. To reduce heat losses, a blanket of rock wool (100 mm) is wrapped over the reactor wall. The gasifier is equipped with an ignition port situated at the throat level and a grate-shaking device. 6 K-type thermocouples were inserted at different locations along the reactor to measure and monitor the temperatures on the different reaction zones. A mass flow meter is used to measure the air blown into the gasifier. The flow of air was regulated using a manual valve and it was uniformly distributed inside the reactor through multiple nozzles.

The product gas at the outlet of the setup was analyzed every 1 min using a 3100 SYNGAS analyzer. This device is equipped with three different cellules that enable the measurement of hydrogen, carbon monoxide, carbon dioxide, methane and oxygen fractions in the gas. Nitrogen fraction is computed by difference. A vacuum pump sucks up the gas to be analyzed continuously inside the analyzer. To ensure the complete removal of tar, dust and water vapor from the gas before the analysis, the sample crosses a cooling and cleaning train consisting of a cooler, a water bubbler, an activated carbon bed and a fine particulate filter.

2.3. Procedure

The experimental tests were carried out following these sequential steps: First, the gasifier was filled with about 5 Kg of wood char. Then, a specified and weighed amount of almond shell (50 kg), which will determine the duration of the run and will be used for the estimation of the average fuel consumption rate, is added. The top cover is then closed and sealed properly. The feed was then ignited using a premixed flame introduced through the ignition port. The flame is hold inside until one makes sure that the fire is spread in that reactor cross section. This may take about 5 to 10 min. Once the almond shell is ignited, the flame is taken off and the ignition port is tightly closed. The air blower is then turned on, and that moment marks the beginning of the experimental run.

The acquisition of the temperature values is started upon the beginning of the run, while gas sampling and analysis is started when stable conditions were established. During the experimental run, the grate was shaken from time to time to remove the residual ash and unburned char. Some shots were applied on the gasifier external walls to prevent the bridging of the almond shell particles at the throat level, i.e. to help the fall of the feed down in the combustion and gasification zones. Table 2 summarizes the experimental conditions of the actual gasification experiments.

Figure 1.a: The pilot scale biomass downdraft gasifier

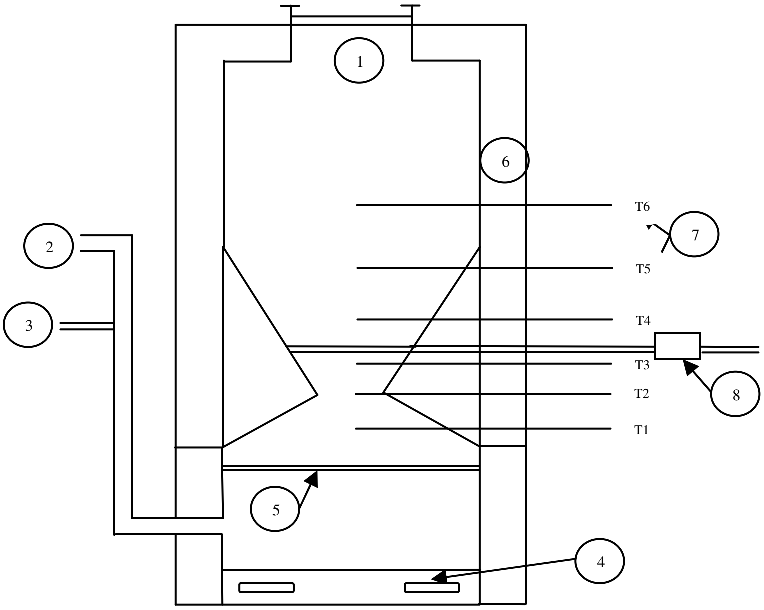

Figure 1.b: Schematic diagram of the gasification setup (1) biomass input (2) product gas outlet (3) gas sampling line (4) ash drawer (5) perforated grate (6) insulation material (7) thermocouples (8) air flow meter

Table 2: Gasification experimental conditions

Biomass	air flow rate (Nm^3.h^{-1})	fuel conversion rate (kg.h^{-1})	air/fuel ratio used	Stoichiometric air/fuel ratio	Equivalence ratio
Almond shell	18	9.25	2.34	5.53	0.42

3. Results and discussion

3.1. Temperature distribution within the gasifier

Figure 2 shows the temperature profiles produced by the thermocouples in the different positions along the gasifier as function of time. At the beginning of the experiment, all temperatures are constantly raising. This experimental time corresponds to a transient period. After approximately two hours, temperatures within the combustion and reduction zones (T1, T2 and T3) reach a high temperature level around 800°C and vary slightly in a specified narrow range. This could be considered as a steady or pseudo steady state regime. Figure 2 shows also that a longer time is needed for the temperatures in the drying and pyrolysis zones to increase. After about three hours, they reach the pseudo steady state regime. This delay could be explained by two reasons: the first is that heat transfer is very limited in the upward direction. Indeed, the virgin biomass has a low thermal conductivity and contains some moisture. The heated layer close to the combustion zone is continuously supplied to the downer zones which reduce the heat propagation in the upward direction. The second is the thermal inertia of the gasifier. Initially, the heat is absorbed by the gasifier body, and when the thermal inertia is overcome, the biomass in the pyrolysis and drying zones starts to be heated up.

We can conclude that the four zones or layers in the gasifier (namely drying, pyrolysis, combustion and reduction) become developed and clearly observed after three hours. So the gasifier performance has to be studied and evaluated after this initial starting period.

3.2. Mean temperature distribution

Temperatures in the combustion and gasification zones fluctuate and overlap even in the steady state regime as shown in figure 2. This could be explained by the non homogeneity of the biomass particles as well as the shakes applied to the grate, which results in a mixing of the bed particles and shifting of the oxidation and gasification reactions sites. Similar observations were found previous works [10, 11]. To get a representative temperature value in the different positions, the mean average temperature in each location is estimated over the steady state regime (after two hours for the combustion and gasification zones and three hours for the pyrolysis and drying zones respectively). Figure 4 shows the mean average temperature distribution along the gasifier. The temperature increases from the top to the bottom of the reactor. It exhibits a smooth increase at the top part, and then it rises rapidly when approaching to the air inlet. The intensive combustion reactions in this region cause the temperature increase to the highest level (about 780°C). Accordingly, the highest temperature appears at the inlet of the gasification zone, the temperature decreases then due to the endothermic gasification reactions. These are the Water gas and the Boudouard reactions given respectively by equations (2) and (3).

Water gas reaction: $$C + H_2O \rightarrow CO + H_2 \qquad \Delta H = 14609\, kJ/Kg \tag{2}$$

Boudouard reaction: $$C + CO_2 \rightarrow 2CO \qquad \Delta H = 14372\, kJ/Kg \tag{3}$$

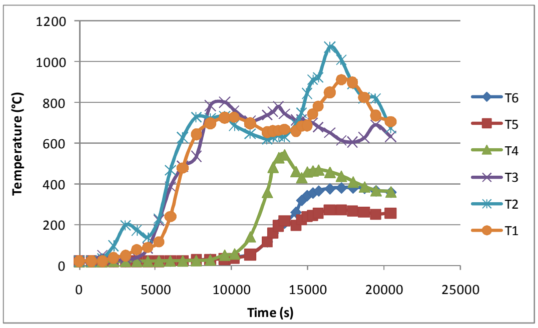

Figure 2: Temperature profiles along the gasifier recorded by the K type thermocouples

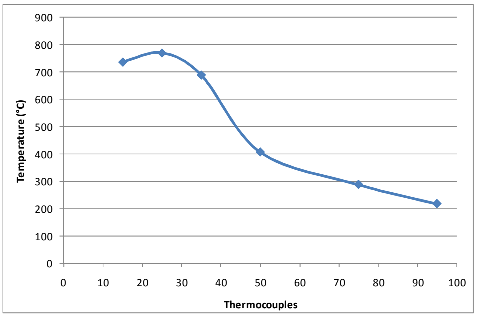

Figure 3: Mean temperature distribution along the height of the gasifier over the steady state period (positions are referenced to the grate level)

3.3. Product gas composition

The generated gas was analyzed at the outlet of the gasifier. Table 2 reports the mean composition averaged over the steady state regime. The carbon monoxide fraction is quiet acceptable and typical while the hydrogen fraction is relatively low compared to previous works [2, 3, 5]. This could be explained by the low oxidation-gasification temperature (less than 800°C). Indeed, the water gas reaction is more active at higher temperatures. A low amount of light hydrocarbons (C_{2+}) was found which suggests that these were decomposed in methane and other gases. The residual oxygen fraction indicates that combustion reactions occurred in the gasification zone, which confirms that these two steps were highly overlapping as shown above with the instantaneous temperature profiles (figure 3).

Table 3: Product gas composition at the outlet of the gasifier (%)

Gas	H_2	CO	CO_2	CH_4	C_nH_m	N_2	O_2
Fraction (%)	8.55	14.37	11.72	3.71	0.19	60.84	0.61

3.4. Gas generator efficiency

The efficiency of the actual gasification experiment is calculated to evaluate the performance of the downdraft gas generator. The process efficiency is defined as the ratio of energy of the product gas per kg of biomass to the LHV of the biomass material. It is given by [8]:

$$\eta_{\text{gasifier}} = \frac{\text{gas production rate}\left(\frac{m^3}{h}\right) * \text{LHV of the product gas}\left(\frac{MJ}{m^3}\right)}{\text{biomass conversion rate}\left(\frac{Kg}{h}\right) * \text{LHV of the biomass}\left(\frac{MJ}{Kg}\right)} \tag{4}$$

The low heating value of the product gas is calculated using equation (8). The fuel conversion rate was defined by equation (7) (see Appendix). The gas production rate is the amount of dry gas ejected at the outlet of the reactor. This flow couldn’t be measured by a flow meter unless it is cooled and cleaned from residual tar and water vapor which requires a big washing and cleaning unit. Here, the gas production rate is simply derived by means of the nitrogen balance between the air blown at the inlet and the obtained gas at the outlet of the reactor (equation 9). This data with the gasification efficiency are presented in Table 4. The gasification efficiency was found to be relatively low which could be explained by the high nitrogen fraction. The operating parameters (essentially the equivalence ratio) could be optimized to ameliorate the heating value of the product gas and consequently the process efficiency.

$$LHV = y_{H2}.LHV(H_2) + y_{CH4}.LHV(CH_4) + y_{CO}.LHV(CO) \tag{5}$$

$$\dot{n}_{gas} = \frac{0.79}{y_{N2}} * \dot{n}_{air} \left(\mathrm{m}^3/\mathrm{h}\right) \tag{6}$$

Tableau 4: Gasification results

LHV_{gas} (*MJ/m^3*)	Gas production rate (*m^3/h*)	Gasification efficiency (%)
4.07	23.388	56.12

4. Conclusion

An experimental investigation of a pilot scale fixed-bed biomass downdraft gasifier was presented in this paper. After an initial transient period of about three hours, a pseudo steady state regime was established in the reactor. The evaluation of the gasifier performance in that regime was conducted. The gas generated from the almond shell contained about 23% syngas (hydrogen and carbon monoxide) with a LHV of about 4 MJ/m^3, which could be considered as low to medium value. The effect of the operating conditions could be studied to retrieve the optimum working conditions of the gas generator and consequently ameliorate the process efficiency.

Appendix

The fuel conversion rate was approximated as:

$$\dot{m}_{fuel} = \frac{\text{amount of the fuel fed in the gasifier} - \text{amount of the fuel left at the end of the run}}{\text{total operation time}} \tag{7}$$

The equivalence ratio is defined as the ration between the air/fuel used in gasification experiment and the one corresponding to stoichiometric combustion of the fuel. It is given by [3]:

$$\Phi = \frac{\left(\text{Air flow rate}/\text{fuel consumption rate}\right)_{\text{used}}}{\left(\text{Air flow rate}/\text{fuel consumption rate}\right)_{\text{stoichiometric}}} \tag{8}$$

The air/fuel ratio corresponding to stoichiometric combustion of the almond shells was calculated using equation (9) on mass basis.

$$CH_{1.63}O_{0.75} + \alpha(0.21.O_2 + 0.79.N_2) \rightarrow \beta CO_2 + \gamma H_2O \tag{9}$$

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