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Process characterization and energy balance of air wood residues gasification using continuous operated pilot scale reactor

Cora Gheorghe-Bulmau*, *Raluca* Nicoleta Tirtea, *Gabriela* Ionescu, *Cosmin* Marculescu
University Politehnica of Bucharest, Department of Energy Production and Use,
Splaiul Independenţei 313, Romania

Abstract. This work aimed to study the effect of gasification process operating conditions on syngas composition and properties, and process efficiency. A rotary kiln gasifier lab-scale pilot plant with capacity ≅ 30 kg/h and a power of 30 kWe was used for gasification tests applied to cherry wood at different loads, for a temperature of about 600°C, while the air was used as gasification agent for all tests. The syngas composition was measured and analyzed. The results have shown that conversion of wood cherry through gasification lead to a lean fuel gas of 3.5 MJ/Nm^3 and installation characteristics have a major influence both on process and syngas properties. This is happened because the rotary kiln gasifier allows some air infiltrations, and consequently a high N_2 content in the syngas composition. The energy balance of the cherry biomass gasification processes was calculated. It was found also that gas density varies slightly from 1.26 to 1.43 kg/m^3, while the specific heat of the gas varies from 1.04 to 1.34 kJ/kgK.

1 Introduction

Wood biomass presently dominates the renewable energy sources for different uses in heat and power generation, transport fuels production [1, 2], wood and wood products accounting for 6.0 % of the total energy consumed within the EU in 2016 [3]. Referring on biomass in the wood processing sector, it can be said that it continues to be an unexploited source of the wood biomass potential. There are significant amounts of wood residues generated by wood-processing industry, produced by manufacturing of veneer, furniture sawn and timber. A considerable part of these residues is generally used on site for energy in factory driven heating installations or sold directly to energy producers [4]. Since one of the late focuses of policy makers is development and deployment of enabling technologies to facilitate the integration of variable renewable energy, residues from wood processing industry may be a viable source for energy production. The furniture industry is the most complex activity of the wood industry and the most performing [5] and depends on the regional differences in wood by-products flow due to diversification of forestry resources, wood –processing industry and pulp-industry around Europe (Figure 1).

* Corresponding author: cora4cora@gmail.com

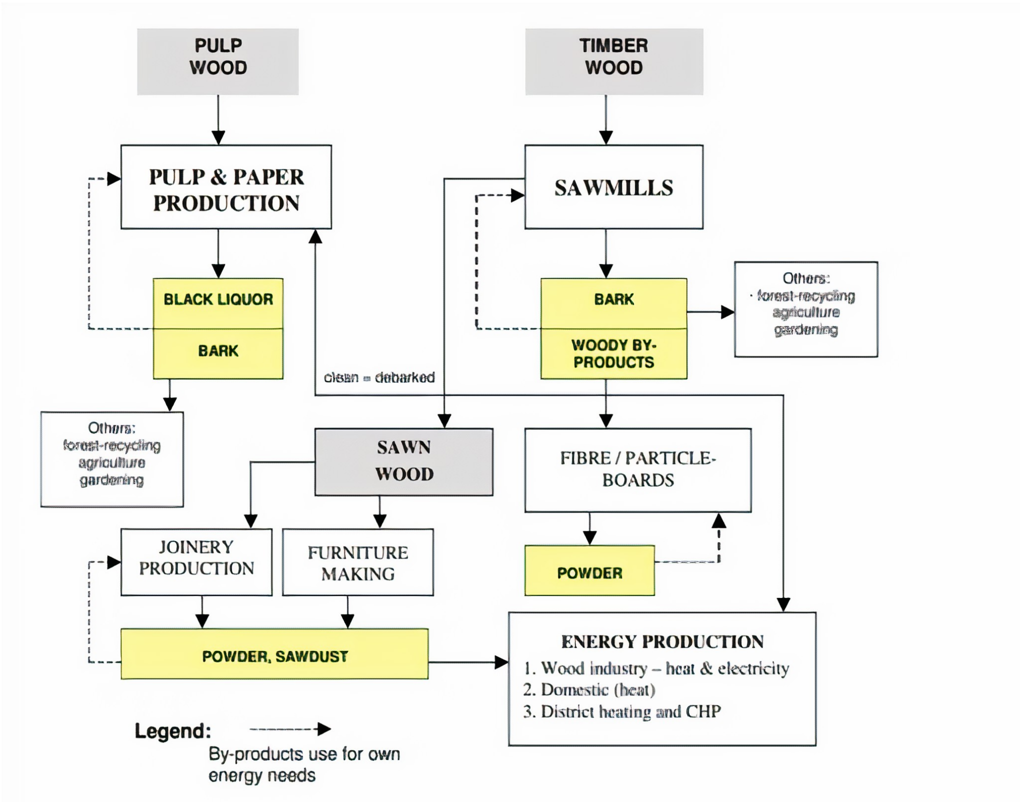

Fig. 1. EU market demands and flows of wood-industry by-products [Eurostat, 2018] [3]

In Romania the furniture manufacturing activity is well represented among the EU states, occupying the third position in 2018 [6]. The main wood species used for furniture industry in Romania are: solid oak, but also beech, cherry, maple, chestnut, fir-tree etc. As furniture industry may very well choices cherry wood, the resulted cherry wood residues may be a considerable resource and so its potential, unexploited, can be valuable with different direction of use.

Gasification is an advanced thermal conversion process that produces a combustible gas obtained from different solid fuels, this being the key of its importance [7]. There are various ways for use of gasification process, and this can be integrated into many systems. The more often application of gasification process is for energy production and electricity in cogeneration stations. Biomass gasification technologies met a rapid development due to constantly diminishing of the fossil fuel resources use along with a constant increase in the demand for electricity [8]. Over incineration, gasification has viable advantages because of the flexibility in the way in which the energy is utilized. Moreover, there are many possibilities for syngas use: it can either be combusted directly, used as a fuel in gas engines/turbines, stored, or processed through catalytic processes (for example, Fischer-Tropsch) to produce liquid fuels or chemicals. The quality and quantity of syngas depends on gasifying agent, that can also affect the composition of the gas, tar content, and heating value [9 - 11]. A widely gasifying agent is air because it is cheaper than other gasifying agents and it is easy to provide to the systems. But use of air as gasification agent lead to a syngas, which comprises large amounts of nitrogen and therefore reduces the heat of the gas combustion [8]. Recently some studies have been published in order to validate the design and to optimize the operation conditions of biomass gasification processes [12 – 14].

From these a conclusion raises: the unit design represents one of the most important factors in determining the syngas quality and heating value [15]. Updraft, downdraft, and CFB gasifiers provide a maximum efficiency of about 75 %, while the maximum energy output is 2.7 MW, 1.1 MW, and 11.1 MW, respectively [16]. Both fixed-bed and downdraft gasifiers are appropriate for producing low heating value gas [17 – 19], first in case of medium size applications [18, 19], the second for generating electricity of small-scale systems in the range of 10 kW up to 1 MW [18 - 21].
This research evaluates the feasibility of using cherry wood biomass in a developed gasifier at semi-industrial scale and how process operational conditions affect the properties of the syngas or the global efficiency of the process. The results generated from the gasification tests indicated differences in the composition, density and calorific value of the syngas produced from the wood biomass and revealed also the impact of equivalent ratio on process energy efficiency.

2 Material and Methods

Data implying the presentation, analysis and characterization of the feedstock used in the current research have been already summarized in a previously manuscript [22]. The gasifier specifications and experimental set-up applied during this research were also described in detail. Here follows a short presentation of these. Tests of cherry wood air gasification were operated in a rotary kiln reactor lab-scale pilot plant. The reactor has a capacity of 30 kg/h, a power of 30 kWel and it allows the variation of the feedstock feeding rate, rotation speed of the reactors, inclination degree, and temperature. In the current tests, air gasification (co-current configuration mode) was applied on cherry wood, at 600°C, the reactor being set at 10° inclination. The modified process parameters were the reactor rotation speed, the biomass and air feeding rate. The syngas was passed through an ice water cooling system, while the composition of the non-condensable fraction has been analyzed using Testo-350XL (real-time measurements) and micro -gas chromatograph-Micro-GC Fusion, Inficon (time-sequential measurements). Testo 350XL gas analyzer cannot determine simultaneously the Hydrogen and hydrocarbons concentrations, therefore only the Hydrogen concentration was determined. In the cases where the micro gas-chromatographer (Micro-GC) was used, the presence of Methane, Ethane and Propane were detected. Based on the measurements, the average syngas compositions were determined.

To establish the mass balance of the process, ash and tar were collected and weighted for each gasification process. Ash was collected in a water vessel in order to be cooled immediately and not to react in the presence of air. Afterwards, the ash was dried, weight and analyzed. The tar fraction was trapped in the condensing system placed between the gasification reactor and gas extraction and sampling [22]. The tar was also weight and analyzed.

When exiting the gasification reactor, syngas has important sensitive energy content. Regenerative applications use this sensitive energy of the syngas. For this type of applications, hot-gas efficiency (HGE) is computed according to equation (1). HGE takes into account both chemical and sensitive energy content of the gas [23 - 26]:

$$\mathrm{HGE} = \frac{\mathrm{LHV_{gas}} \cdot \mathrm{M_{gas}} + \mathrm{M_{gas}} \cdot \mathrm{c_{gas}} \cdot (\mathrm{T_{gas}} - \mathrm{T_{ref}})}{\mathrm{LHV_{fuel}} \cdot \mathrm{M_{fuel}}} \quad (1)$$

where: LHVgas/LHVfuel is the low heating value of gas/fuel [kJ/kg]; Mgas [kg] is the mass of gas produced from gasifying a specific amount of fuel Mfuel [kg]; c_{gas} [kJ/kgK] is the specific heat of gas; Tgas is the gas temperature exiting the reactor [°C], and Tref is the reference temperature [°C].

3 Results and discussion

In gasification processes the reactor type has major influence on syngas properties. Rotary kilns are not utilized in gasification processes because of air and fuel poor mixing level. They are currently used in pyrolysis processes or cement industry. Nevertheless, the process evolution trend can be observed and modified in real time because of continuous operation of the pilot reactor used in our study. The differences between our results and other studies are because of reactor type, but the influence of process parameters on reaction products are following other research studies [27, 28].

3.1. Syngas composition

For the first experiment conducted, gas composition was determined using a Testo 350XL gas analyzer, while for experiment no. 2 to no. 6, the gas composition was determined through gas-chromatography. During the first experiment, according to the gas composition, a preponderant combustion process occurred in the reactor. High amount of CO_2 was produced, and unreacted air was found in the gas (O_2 concentration exceed 7 %). CO concentration did not reach 2 %, while the H_2 concentration was below 1 %. All of these are a consequence of a highly amount of air introduced in the process. In the 2nd experiment the equivalence ratio (ER) was reduced and the syngas composition changed considerably (Figure 2). CO_2 concentration has almost doubled, CO concentration increased more than 4 times, while the O_2 concentration was almost zero. H_2 concentration slightly increased from 0.40 % to 0.63 %, but the presence of light hydrocarbons may be observed, of which the most notable is the ethane with a concentration of 1.92 %.

When the ER decreases, and the time residence increases – compared to the first case – (Experiment no. 3 – Figure 3), an improvement in gas quality can be observed. The CO concentration exceeds 10 %, while the H_2 concentration reaches a medium value of 2 %. Carbon dioxide average concentration grows slightly comparing to Experiment no. 1.

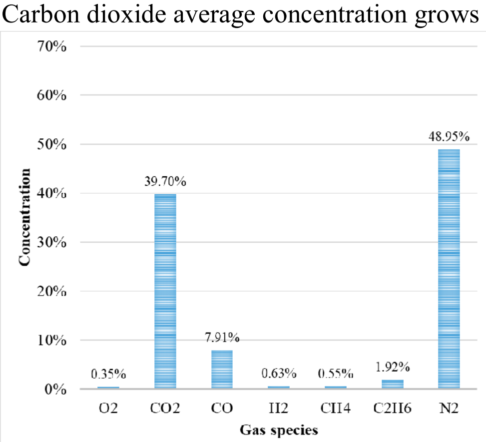

Fig. 2. Syngas composition – Experiment no. 2

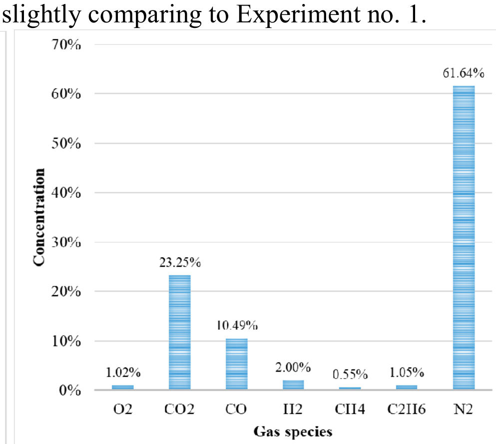

Fig. 3. Syngas composition – Experiment no. 3

In Figure 4 is presented the medium composition of the syngas produced during the 4th gasification experiment. In this case, the ER was further reduced, while the residence time was maintained high. Since less air was present in the reactor and the gases where maintained in the reactor longer, the CO_2 resulted from the combustion stage reacted with the char and more CO was produced. The concentrations of carbon oxides are approximately equal, 18.35 % vs. 17.39 %. Both H_2 and CH_4 concentrations exceed 2 %.

In the 5th experiment (Figure 5) the residence time was slightly decreased, and the ER was almost doubled compared to experiment no. 4. In consequence, CO_2 concentration increased (~ 25 %) and CO concentration decreased (less than 10 %). Hydrogen and methane concentrations also decreased to 1.35 %, respectively 0.67 %. However, the ethane concentration exceeds 1 %.

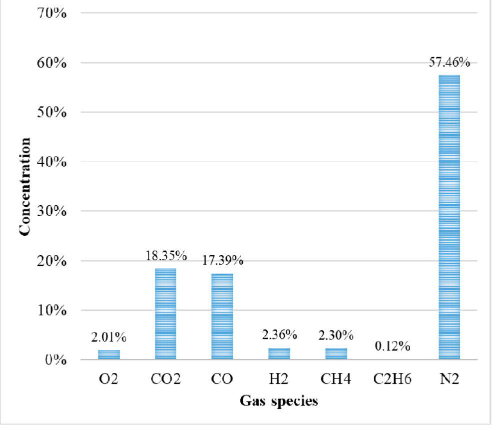

Fig. 4. Syngas composition – Experiment no. 4

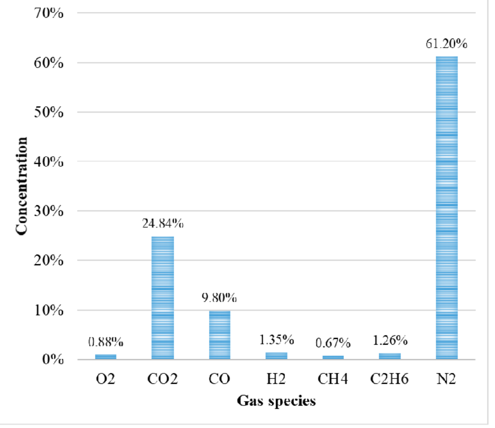

Fig. 5. Syngas composition – Experiment no. 5

In Figure 6 is presented the average syngas composition resulted from the 6th gasification process. Compared to the previous cases the residence time was the highest, and the ER was lowest. CO_2 and CO medium concentration slightly exceeds 20 %, respectively 16 %.

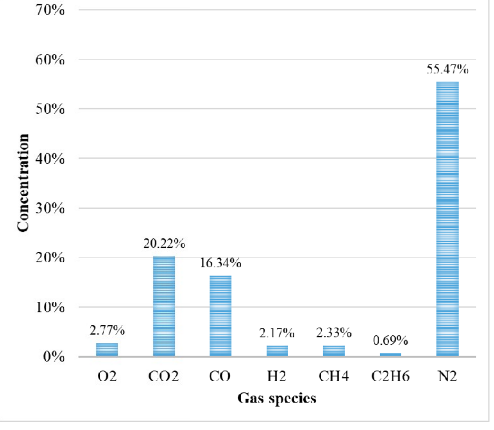

Fig. 6. Syngas composition – Experiment no. 6

According to the carbon oxides concentrations, better results were obtained in the 4th experiment. Hydrogen concentration is also smaller compared to Experiment no. 4 (2.17 %), while the light hydrocarbons concentrations (methane and ethane) are slightly higher (2.33 % vs. 2.30 % and, respectively 0.69 % vs. 0.12 %).

3.2. Syngas properties

Gas properties were determined considering the average composition of the gas presented in the previous section. The low heating value (LHV), density and specific heat of the gas were determined and presented in Figure 7 and Figure 8.

Figure 7 reveals how gas composition influences the heating value of the syngas. Gas heating value increases with combustible gas species concentrations. In the first experiment, the combustion process was preponderant; therefore, the gas heating value has not reached 1 MJ/m^3. The syngas produced from gasification experiments no. 4 and no. 6 registered a heating value that exceeds 3 MJ/m^3, while the heating value of the gas resulted from experiments no. 2, no. 3 and no. 5 is approximately 2.4 MJ/m^3. The highest LHV obtained is of 3.5 MJ/m^3.

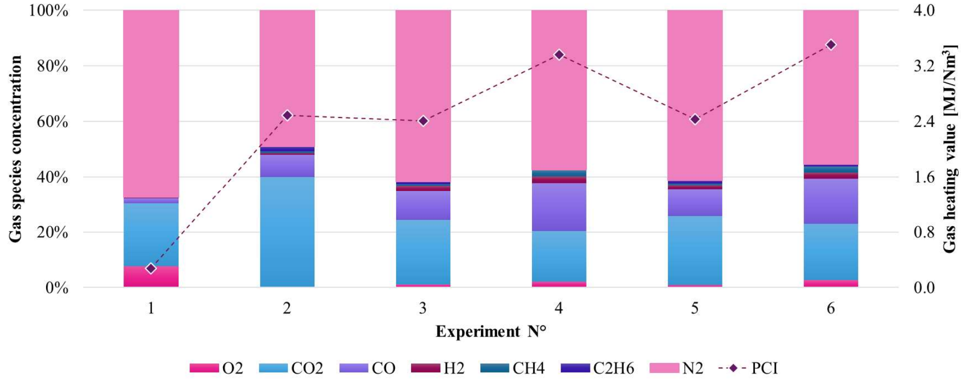

Fig. 7. Low heating value of the syngas as a function of gas species concentration

It is known that use of air as gasification agent lead to a syngas with a high content of Nitrogen, which reduces the LHV of the gas to a value of 3-6.5 MJ/Nm^3 [29]. Although the value obtained from our experiments is low, it follows values already reported by other researchers [27, 28] for syngas resulted from wood and correlated with the gasifying agent (air).

In Figure 8, the gas density and specific heat are presented for the 6 conducted gasification processes. Gas density varies slightly from 1.26 to 1.43 kg/m^3, while the specific heat of the gas varies from 1.04 to 1.34 kJ/kgK. Both density and specific heat are a function of gas composition at normal conditions of temperature and pressure.

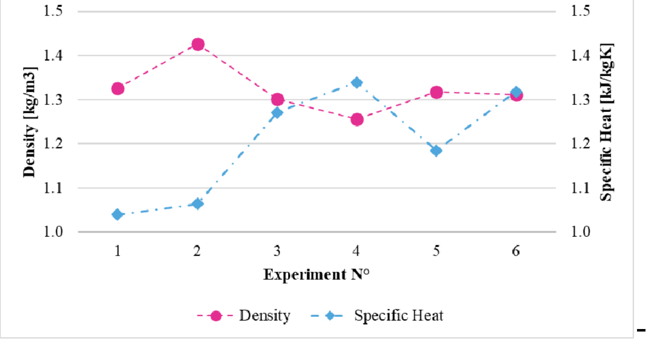

Fig. 8. Density and specific heat of the syngas

Natural gas density at standard temperature and pressure varies between 0.7 and 0.9 kg/m^3 [30], while its specific heat is 2.34 kJ/kgK [31]. Compared to the types of syngas presented in this paper, natural gas has lower density, but higher specific heat.

3.3. Mass and energy balance

For each gasification experiment, mass and energy balance were determined. According to mass balance (Figure 9) gas production ranges between 93.31 % and 98.23 %, while the tar production averages 1.18 % and the ash production averages 2.81 %.

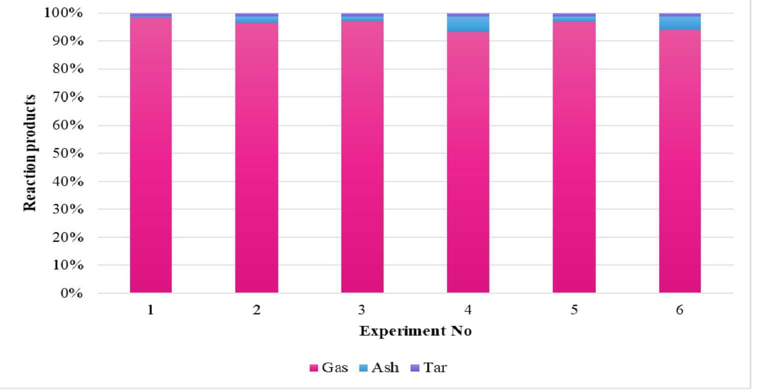

Fig. 9. Reaction products distribution of the gasification experiments

Highest gas production corresponds to the first experiment conducted which is characterized by the highest ER. Lowest gas production 93.31 % and 93.89 % correspond to experiment no. 4 and no. 6, when the ER value set was at its lowest. Even though the gas production is lower in these two cases, the LHV of the gas was considerably higher (Figure 7). Tar production varies slightly between 1.15 % and 1.20 %, while the ash had a quota of 0.59 – 5.53 % (experiment no.1 and, respectively no. 4) of all reaction products.

In Figure 10, the input and output energy flows of the gasification reactor are presented. Experiments no. 2, no. 3 and no. 5 are similar regarding the input/output energy flows values, but their process energy efficiency varies between 69.04 % and 74.08 %. As it is mentioned above, the syngas resulted from these three experiments have a medium LHV, compared to the other experiments conducted, but these processes registered the highest energy efficiency.

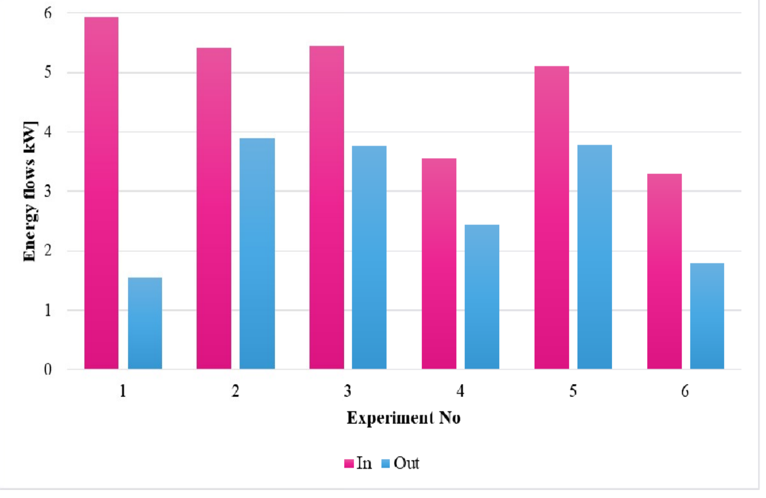

Fig. 10. Energy balance of the gasification experiments

Colum 1 in Figure 10 corresponds to combustion process, being out of range of current gasification energy efficiency. The process energy efficiency of experiment no. 4 and no. 6, which corresponds to the highest gas LHV, was 68.28 % and, respectively 54.39 %.

Wood gasification in rotary kiln reactors it is not preferred due to lack of proper agent – feedstock mixing. Improper mixing of input flows, and between the gas phases, leads to low carbon conversion efficiencies. In the gasification experiments conducted, the ash Carbon content varied from 10 to 27 %. Therefore, process energy efficiency determined resulted quite low.

The low energy efficiency can be also explained through the absence of air preheating before injection into reactor leading to a cooling effect and oxidation reactions delay.

4 Conclusions

Continuous operated reactors offer undeniable advantages in process observation over batch or fed-batch reactor. The real time gas sampling and process parameters monitoring give accurate information on process run and reaction products formation. While the collected are closer to industrial ones, the reactor / installation type strongly influences the process and restrains the validity of the results to the specific experimental set-up. The rotary kiln reactor used in the study introduced a series of perturbations through the false air infiltration and low fuel-air mixing level but enabled the precise control and observation of the process.

The results show, as expected, the importance of Equivalent Ratio on process energy efficiency as well as on carbon conversion ratio. Low values of ER led to a longer residence time in the rotary kiln reactor and so a longer reaction between the CO_2 resulted from the combustion stage reacted and char leading to high CO production.

Mass balance indicated a gas production in the range of 93.31 % and 98.23 %, while the average production for tar registered a value of 1.18 % and of 2.81 % for ash, respectively.

The calculated value of gas density recorded a slow variation from 1.26 to 1.43 kg/m^3, while a reduced difference was obtained for the gas specific heat of the gas, between 1.04 and 1.34 kJ/kgK. The results show that process energy efficiency is not sufficient for gasification process, as it is for combustion, and it must be correlated with the syngas specific energy content. The process energy efficiency maximized at 74 %, while de syngas LHV was maximum when the process energy efficiency was about 55 %.

Relevant information on air-gasification process was achieved with respect to operating parameters, syngas quality and global energy efficiency.

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