Experimental study of the co-gasification of wood and polyethylene in a two-stage gasifier

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Abstract
Co-gasification of wood mixed with 20% (mass fraction) of polyethylene (PE) in a two-stage NOTAR® fixed-bed gasifier was studied in the present paper. The ratio of air flow injected in the pyrolyzer and air flow injected in the oxidation zone is called the air ratio (AR). The AR of 0.35, 0.43, and 0.49 were used for test runs. Mass and energy balances were established. The study showed the feasibility of co-gasification of wood mixed with 20% of PE in the two-stage gasifier. However, considerable quantity of residues rich in fixed carbon content (17% of the fuel mass and 69% of fixed carbon content) was produced due to a low reactivity of the charcoal obtained after the pyrolysis. AR increasing reduces the gas CO content due to overconsumption of char at the pyrolysis stage. H₂ and CH₄ highest values are obtained for the intermediate AR = 0.43 which maximized the LHV, energy efficiency, and carbon conversion with respectively 4674 kJ/Nm³, 64.35%, and 74.52%. Low reactivity and carbon content of the pyrolysis char likely lead to lower performance of co-gasification of PE mixed with wood compared to wood gasification.

KEYWORDS
air ratio, co-gasification, polyethylene, two-stage gasifier

1 | INTRODUCTION
The diversification of the energy sources has a great interest in order to deal with a steadily growing of energy demand all over the world. The energy recovery from biomass and waste has gained much attention for research particularly by the gasification process. Biomass gasification technology has the advantage that it can be a clean and very efficient conversion process which allows the valorization of a wide range of biomass and waste. There are also gasifiers which do not fulfill this statement. In case of fixed-bed gasifiers, wide range of biomass and waste is limited. Biomass and waste can be gasified together in the co-gasification process. Indeed, a huge quantity of waste is available due to a growth of the demography and the consumption mainly in African countries. The management of the waste produced is a great challenge for these countries, particularly the plastic waste made of polyethylene (PE). Thus, the co-gasification of wood and PE waste was investigated in the present paper.

Biomass and PE co-gasification studies were mostly carried out with steam or with a mixture of air and steam as gasification agent. In addition, the fluidized bed gasifier was largely used for the gasification of PE alone or mixed with wood or coal since it is more suitable for the plastic
feeding and the gasification process comparatively to the fixed-bed gasifier. Synergetic effects were notified by some authors during the co-gasification of wood and polyethylene. Yang et al. showed a decrease of the reaction activation energy during the co-gasification of rice straw and PE. The synergetic effect also enhanced the H2, CO and CO2 molar fraction during the steam co-gasification of plastic and biomass according to the results obtained by Burra and Gupta. García-Bacaicoa et al. worked on the co-gasification of PE in a small-scale fixed-bed gasifier. The mass proportions of PE used by these authors vary from 0% to 17.4%. They found that the PE increases the calorific value of the product gas. The same result was found in experiments conducted by Pinto et al. However, technical problems were reported during the co-gasification of wood with polyethylene, in particular at high mass proportion (superior to 20%) of PE. Yang et al. showed that PE clogs the biomass structure during the pyrolysis and reduces the degradation rate of the mixture comparatively to the gasification of pure biomass or pure PE. Furthermore, other authors had recently revealed the decrease of the carbon conversion efficiency due to the PE during the co-gasification with wood. Therefore, the proportion of plastic in the gasification must be limited in order to avoid a malfunction of the gasifier. Thus, in this study, the PE mass fraction of 20% was used for the co-gasification test runs.

Note that the downdraft two-stage fixed-bed gasifier, used in the present study, is more flexible than one-stage fixed-bed gasifier and is thus suitable for a wider range of solid fuels such as natural wood, rubber from tires, and sludge. The most important parameter of the gasification process in the two-stage gasifier is the air ratio defined as the ratio of air injected in the pyrolysis zone on the air injected in the oxidation zone, since it can increase the gas calorific content and allows a drastic reduction of the gas tar content. The study conducted by Martinez et al. in two-stage biomass gasifier has shown a strong impact of the air flow on the process. These authors found the optimum conditions of the gasification with an equivalence ratio of 0.4 and high AR equal to 0.8. The same optimal AR (0.8) was found, in a similar reactor, by Galindo et al. The high temperature achieved in the pyrolysis and combustion zone favored the higher performances of the two-stage gasification comparatively to the single stage one. However, for the NOTAR® technology, the gasifier used in the present study, the AR is an important parameter and must be kept as low as possible during the biomass gasification according to Jeanmart et al.

The current work aims to test the feasibility and to optimize the performances (LHV and energy efficiency) of the co-gasification of wood mixed with 20% of PE in the NOTAR® gasifier. The impact of AR on the gas composition, the LHV of the gas, and the energy efficiency were studied during these test runs. In addition, the mass, chemical elements, and energy balances were done during the study. The co-gasification process of PE and wood was finally analyzed comparatively to the gasification of biomass alone.

### 2 Materials and Methods

#### 2.1 Characteristics of fuels

The used fuel is a mixture of poplar wood chips and small polyethylene balls coming from the plastic bag manufacturing industry. Wood and PE proximate and ultimate analysis are presented in Table 1.

PE was ground in order to facilitate the fuel feeding in the gasifier. The prevailing temperature during the grinding process had transformed the plastic PE into granules form (due to its low fusion temperature). Figure 1 shows the wood and PE conditioned for the gasifier feeding. Wood and PE were manually mixed before to be feed in the gasifier.

#### 2.2 Materials

Figure 2 shows the two-stage gasifier device used in the present study. The gasifier has a high thermal inertia due to a large amount of concrete used to insulate the gasifier. The gasifier is a scale down of an industrial one and uses the same

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**Table 1** Ultimate and proximate analysis of poplar wood and PE

| Fuel    | Wood | PE |
|---------|------|----|
| Ultimate analysis (%) |      |    |
| C       | 45.5 | 85.5 |
| H       | 6.26 | 14.2 |
| N       | 1.04 | -   |
| O       | 47.2 | -   |
| S       | -    | 0.3 |
| Proximate analysis (%) |      |    |
| Humidity | 9.60 | -   |
| Ash (db) | 3.70 | 0.0 |
| Volatile matter (db) | 75.54 | 99.4 |
| Fixed carbon (db) | 11.50 | 0.6 |

Abbreviations: daf, dry and ash free basis; db, dry basis.
amount of insulation. Thus, the establishment of the gasification reaction takes many hours. The gasifier is composed by, from top to bottom, a drying and pyrolysis zone, an oxidation zone, and a reduction zone. A physical separation isolates the pyrolysis zone from the two other reaction zones contrarily to other types of two-stage gasifiers where there is no physical separation between the pyrolysis and the reduction zone. The operating details of the gasifier are provided in previous works.10,14 The gas was sampled after the sawdust filter in order to analyze the mole fractions of CO, CO₂, CH₄, and H₂. The fraction of N₂ is determined by difference. A Hartmann gas analyzer was used to measure the volume fractions of the gas produced by the co-gasification. The principle of operation of the gas analyzer is based on Lambert-Beer law. The gas was determined based on the radiation wavelength ranging from 2 to 8 μm. A total of 18 K-type thermocouples were placed in the gasifier for temperature measurement during the co-gasification test runs. The thermocouples were placed at each 9 cm along the gasifier.

Figure 3 shows the positioning of the thermocouples and the air inlets on the gasifier. Eleven thermocouples were placed in the pyrolysis zone, three in the oxidation zone, and four in the reduction zone. The operation of the gasifier is automated and controlled by a program developed with LabVIEW® from National Instrument.

### 2.3 | Methods

#### 2.3.1 | Gasification process

The fuel feeding in the gasifier and the ash removing are done sequentially. The gasifier feeding is automated, and the number fuel feeding sequences is recorded for each gasification test run. The ash is discharged via an endless screw and then accumulated into a container connected to the rest of the apparatus by a water seal. This allows the continuous measurement of the ashes weight thanks to a balance placed under the ashes container. At the outlet of the gasifier, the gas passes through a dust cyclone and then in a wet scrubber where a cleaning water is injected to quench the gas to a temperature below 100°C. The gas then flows through a counter-current heat exchanger to cool the cleaning water and to condense the steam contained in the gas. At the exit of the heat exchanger, the gas is cooled to a temperature of ~20°C (Figure 2). The excess of the condensed water coming from the produced gas is regularly discharged into another container. The saturated gas obtained at the heat exchanger exit passes through a wet cyclone to remove droplets of water that could had been entrained and then through a granular filter which acts as a final filter to remove the particles that could still be entrained by the gas flow. The cleaned syngas can then be directed to two types of engine or to a flare, depending on the experiments. In this case, as the aim was to focus on the gasification process, it was directed to the flare.

The NOTAR® gasifier is a two-stage design. It has three reactive zones, two physical zones, and two air injections. Note that, for the classical downdraft gasifier, the air is injected only the oxidation zone; thus, the key factor is biomass to fuel ratio. For the two-stage gasifier, the same air flow (which may be used for the classical gasifier) is injected at two different parts of the reactor: the pyrolysis zone and the oxidation zone. The primary air is injected in the pyrolysis zone, and the secondary air is injected in the oxidation zone. As a consequence, we have to find the suitable repartition between the primary and secondary air flow. Primary air allows the fuel pyrolysis by providing the needed heat due to the combustion of a fuel fraction. The primary air flow is smaller than the secondary air flow in order to avoid the combustion of char in the pyrolysis zone. The air distribution between the two stages of the gasifier plays an essential role in the gas quality. An air ratio (AR) was introduced to designate the average of the air flow ratio in the pyrolysis zone to the average air flow in the oxidation zone (Equation (1)).

\[
AR = \frac{\text{mean air flow injected in the pyrolyzer}}{\text{mean air flow injected in the oxidation zone}}
\] (1)
The gasifier is preheated and the measurements only begin when a steady state is reached. Analysis of the co-gasification process (mass and energy balances, energy efficiency, etc) can only be performed during the steady state. Three co-gasification test runs were conducted by varying the air ratio. The mixture contained 20% of PE and 80% of wood in mass fractions.

2.3.2 Mass and elementary balances

The mass balances were made, for the co-gasification test runs, taking into account the mass of wood and PE, air, gas, residues, and water vapor (Equation (2)).

\[ m_{\text{fuel}} + m_{\text{air}} = m_{\text{gas}} + m_r + m_v \]  

(2)

The estimation of the mass of the fuel mixture was performed based on the number of the sequences \( N_{\text{seq}} \) and the average mass \( m_{\text{fuel/seq}} \) of the fuel mixture introduced into the gasifier for one sequence (Equation (3)). A sequence was defined by the solid fuel feeding system.

\[ m_{\text{fuel}} = N_{\text{seq}} m_{\text{fuel/seq}} \]  

(3)

As the gasifier presents a slight overpressure (20 000 Pa), the biomass feeding is made through an airlock. A sequence corresponds to the consumption of the wood volume contained in one airlock. \( m_{\text{fuel/seq}} \) was obtained by the ratio of the total mass of fuel introduced in the hopper to the total number of the filling sequences recorded during the experimental campaign. The air and gas masses were calculated with the Equations (4) and (5), respectively. The ideal gas law was used to determine the molar volume \( (\text{m}^3/\text{mol}) \) at each temperature (Equation (6)). The gas volume and the nitrogen density were given, respectively, by Equation (7) and Equation (8).

\[ m_{\text{air}} = \rho_{\text{air}} \left( T_a / T_0 \right) V_{\text{air}} T_0 / T_a \]  

(4)

\[ m_{\text{gas}} = \left( V_{\text{gas}} / V_m \right) \sum n_i M_i \]  

(5)

\[ V_m = RT / P_a \]  

(6)

\[ V_{\text{gas}} = \left( 0.79 \times \rho_{\text{N}_2} \left( T_a / n_{\text{N}_2} \rho_{\text{N}_2} \left( T_{\text{gas}} \right) \right) \right) \times V_{\text{air}} \]  

(7)

\[ \rho_{\text{N}_2}(T) = M_{\text{N}_2} P_a / RT \]  

(8)

The mass of the moisture contained in the gas was determined by the sum of the mass of removed water \( m_{\text{water}} \) in the gas cleaning system and the steam mass contained in the saturated gas (Equation (9)).

\[ m_v = m_{\text{water}} + w_{\text{sat}} m_{\text{gas}} \]  

(9)

The residues mass was determined by the difference of the mass of ash container before and after the gasification test.
Mass balance of each chemical element was carried out in the present study. The masses of carbon, hydrogen, oxygen, and nitrogen in the reactants were determined by the following Equations (10)-(13):

\[
m_{\text{Carbon}}^{\text{in}} = m_b \left(1 - t_{b} - t_{ash_b}\right) \% C_b + m_{PE} \left(1 - t_{ash_{PE}}\right) \% C_{PE}
\]

\[
m_{\text{Hydrogen}}^{\text{in}} = m_b \left(1 - t_{b} - t_{ash_b}\right) \% H_b + m_{PE} \left(1 - t_{ash_{PE}}\right) \% H_{PE}
\]

\[\quad + 2/18 \times \left(m_b t_{h_b} + m_{h_{air}}\right)
\]

\[
m_{\text{Oxygen}}^{\text{in}} = m_b \left(1 - t_{b} - t_{ash_b}\right) \% O_b + 32 \times 0.2 \frac{m_{\text{air}}}{29}
\]

\[\quad + 16/18 \times \left(m_b t_{h_b} + m_{h_{air}}\right)
\]

\[
m_{\text{Nitrogen}}^{\text{in}} = m_b \left(1 - t_{b} - t_{ash_b}\right) \% N_b + 28 \times 0.8 \frac{m_{\text{air}}}{29}
\]

\[
m_{\text{Carbon}}^{\text{out}} = 0.012 \left(n_{CO} + n_{CO} + n_{CH}\right)
\]

\[\quad \times V_{\text{gas}} / V_m + m_r \left(1 - t_{ash_r}\right)
\]

\[
m_{\text{Hydrogen}}^{\text{out}} = 0.002 \left(n_{H_2} + 2 n_{CH}\right) \times V_{\text{gas}} / V_m + (2/18) \frac{m_{v}}{}
\]

\[
m_{\text{Oxygen}}^{\text{out}} = 0.016 \left(n_{CO} + 2 n_{CO_2}\right) \times V_{\text{gas}} / V_m + (16/18) \frac{m_{v}}{}
\]

\[
m_{\text{Nitrogen}}^{\text{out}} = 0.028 n_{N_2} \times V_{\text{gas}} / V_m
\]

The chemical elements balance was based on the mass balance. The residues from co-gasification are supposed to contain only carbon and ashes. Thus, proximate analysis of the co-gasification residues and PE was conducted in the present study in order to get their carbon and ash content. The proximate analysis was performed using a Heraeus muffle furnace and by following the standards given by XP CEN/TS 14775.\textsuperscript{15} and XP CEN/TS 15148.\textsuperscript{16}

### 2.3.3 Energy balance

The energy balance usually involves the energy input, output, and lost during the gasification test runs (Equation (18)).

\[
E_{\text{fuel}} + E_{\text{air}} = E_{\text{gas}} + E_r + E_r
\]
The energy contained in the fuel is the sum of the energy of wood and PE. The sensible and chemical energies were considered for the calculation of the energy of biomass and gas. The energy of wood, PE, air, and gas were computed by Equations (19), (20), (21), and (22), respectively.

\[ E_h = m_h \left[ (1 - t_{ash}) \left( LHV_h + c_{pa} (T_a - T_0) \right) + (t_{ash} c_{pa} + t_{ash} c_{paw}) (T_a - T_0) \right] \]  

\[ E_{PE} = m_{PE} \left( LHV_{PE} + c_{PE} (T_a - T_0) \right) \]  

\[ E_{air} = (V_{gas} / V_m) \left( 0.21 \times h (T_a) O_2 + 0.79 \times h (T_a) N_2 \right) \]  

\[ E_{gas} = (V_{gas} / V_m) \sum n_i \left( LVH_i + h (T_{gas}) \right) \]  

The sensible energy of the gas species and the carbon (graphite form) were computed by the enthalpy difference at the temperatures considered, \( h (T_i) \), and at the reference temperature, \( h (T_{ref}) \); \( h (T) \), values were summarized in JANAF thermodynamic tables. \( h (T_{ref}) \), is equal to zero at the reference temperature of 298.15 K which was considered in the present study. The energy lost in the ash and the unconverted carbon was estimated based on the ash content of the biomass and the residues mass obtained after the co-gasification trial (Equation (23)). The steam energy contained in the gas is given by Equation (24).

\[ E_r = \left( m_r - m_h t_{ash} \right) \left( LHV_{carbon} + h \left( T_{carbon} \right) \right) \]  

\[ + m_h t_{ash} c_{paw} \left( T_{gas} - T_0 \right) \]  

\[ E_v = m_v \left( L_v + h \left( T_v \right) \right) \]  

The energy gap (\( E_{gap} \)) was given by the difference of the input and output energies (Equation (25)). Note that the energy loss through the reactor walls was included in the energy gap since it was not computed.

\[ E_{gap} = E_{fuel} + E_{air} - E_{gas} - E_v - E_r \]  

The data used for the calculation are summarized in Table 2.

3 | RESULTS AND DISCUSSION

3.1 | Co-gasification performances

The co-gasification test runs were done with a mixture of 20% of PE and 80% of wood (mass fractions) and for three air ratios, as said before. Figure 4 shows the average temperature in the pyrolyzer, the oxidation zone, and the reduction zone during the co-gasification test runs. The temperature fluctuations are mainly related to the variation of air flow as shown by Figure 5 (for the intermediate AR = 0.43). The pressure drop fluctuations along the entire device were the principal cause of air flows fluctuations. The fuel supply sequences in the pyrolyzer and the ejection of char from the pyrolysis zone to the reduction zone caused also a fluctuation of temperature and gas composition. The gas obtained from the gasification is used for analyses once the process reached a steady-state phase. Thus, the analyses of the co-gasification performances were conducted during the steady state phase. The steady-state phase and the transitional phase of the gasification were identified based on the variation of temperatures inside the reactive zone. Vertical lines were placed between the transitional phase at the left and the steady-state phase at the right of the lines (Figure 4).

The average temperature in the pyrolysis zone, the oxidation zone, the reduction zone, and the operating parameters of the co-gasification according to the air ratio were calculated during the steady-state phase (Table 3). The equivalence ratio (ER), the air mean flow rate in the gasifier, the volume of the produced gas, the consumed fuel mass per hour, and the ratio of the produced gas volume to the mass of the consumed fuel (\( Y_{gas} \)) were given as operating parameters. Equivalence ratio (ER) is defined as the ratio between the air flow rate supplied and the stoichiometric air flow rate necessary for the fuel mixture complete combustion. The variation of ER was small despite the air flow variation due to the self-adjustment of the fuel and air flow in NOTAR® technology. Thus, energetic performances are influenced principally by the AR.

The greater the amount of injected air into the pyrolysis zone is (i.e., AR increases), the higher is the temperature in this zone. The air ratio has an influence on the whole process. For example, it modifies the gas composition and the charcoal properties (carbon and oxygen content, reactivity) at the outlet of the pyrolysis zone. Thus, pyrolysis plays a key role in the success of the gasification in general and in particular for the NOTAR® technology. The variation of the average temperature from the top to down of the pyrolyzer depending on the air ratio is shown by the Figure 6.

The temperatures peaks in the pyrolysis zone were reached in the middle of the pyrolyzer, and it corresponds to the place where the smoldering combustion occurs. The temperature peaks were largely superior to 450°C (Figure 6). Therefore, the polyethylene first fuse then deteriorates by evaporation in the pyrolyzer. Indeed, Kawaguchi et al. had estimated the PE melting temperature at 111°C and its thermal degradation temperature between 337°C and 447°C. Investigation of co-pyrolysis...
Table 2: Data used for the calculation

| Properties                        | Value | References         |
|-----------------------------------|-------|--------------------|
| Specific heat (kJ kg⁻¹ K⁻¹)       |       |                    |
| Wood                              | 1.5   | Roy et al²⁸        |
| PE                                | 2.50  | Li et al²⁹         |
| Ash                               | 0.84  | Ragland et al³⁰    |
| LHV of solid fuel (MJ/kg)         |       |                    |
| Wood                              | 17.19 | Bartolomé and Gil²¹|
| LHV of fuel gas (kJ/mol)          |       |                    |
| CO                                | 283   |                    |
| H₂                                | 242   |                    |
| CH₄                               | 803   |                    |
| Air density (kg/Nm³)              | 1.292 |                    |
| Latent heat of vapor condensation (kJ/kg) | 2550 |        |

A high air ratio (AR = 0.49) allowed to achieve high temperatures in the major part of the pyrolyzer due to a high air flow in the pyrolysis zone. In contrast, the amount of air injected in the oxidation zone was low for AR = 0.49 and this had affected the oxidation and reduction mean temperature. Indeed, the lowest mean temperature in the reduction zone was obtained for AR = 0.49. The higher mean temperature (of the order of 1000°C) in the oxidation zone was achieved for AR = 0.35 since considerable amount of air is injected in the oxidation zone. But the average temperature along the pyrolyzer is significantly low unless the peak temperature (460°C). This is not favorable to a complete thermal degradation of PE. The temperature in the reduction zone is also low (about 680°C) for AR = 0.35.

An intermediate air ratio (AR = 0.43) led to a high temperature (above 450°C) mainly in the bottom of the pyrolyzer with a temperature peak of almost 550°C, and this allows the conversion of fuels particularly the polyethylene (Figure 6). In addition, the highest temperature in the reduction zone (770°C) was reached with air ratio of 0.43. Based on the temperatures obtained in the different gasification steps, the intermediate air ratio of 0.43 was favorable to a better energetic performances of the co-gasification of wood and PE in this type of gasifier. Gas composition, energy efficiency, and LHV of the gas have been considered as the main energetic performances.

Figure 7 shows the variation of the gas composition with the time, during the steady-state phase of the co-gasification of wood and PE. The observed fluctuations of the gas composition were due to the discontinuous feedstock flow. The raw biomass going from airlock to pyrolysis zone or char going from pyrolysis zone to reduction zone impacted the process particularly the gas composition. This impact on the temperature was limited thanks to the high thermal inertia of the experimental gasifier.
The average values of the gas composition, the LHV, the energy efficiency ($\eta_{\text{gas}}$), and carbon conversion efficiency ($\eta_{\text{carbon}}$) of the co-gasification are presented in Table 4. The gas LHV, the energy efficiency, and the carbon conversion efficiency were calculated by using the Equations (26)-(28), respectively.

$$LHV_{\text{gas}} = n_{\text{CO}}LHV_{\text{CO}} + n_{\text{H}_2}LHV_{\text{H}_2} + n_{\text{CH}_4}LHV_{\text{CH}_4}$$  \hspace{1cm} (26)

$$\eta_{\text{gas}} = \frac{V_{N_{\text{gas}}} LHV_{\text{gas}}}{m_{\text{fuel}} (0.8LHV_b + 0.2LHV_{\text{PE}})}$$  \hspace{1cm} (27)

$$\eta_{\text{carbon}} = \frac{12V_{N_{\text{gas}}} (n_{\text{CO}} + n_{\text{CO}_2} + n_{\text{CH}_4})}{22.4m_{\text{fuel}} (0.8C_b + 0.2C_{\text{PE}})}$$  \hspace{1cm} (28)

$C_b$ and $C_{\text{PE}}$ are, respectively, the carbon content in the wood and the PE given by Table 1. The results show a decrease of CO when the air ratio increases, in contrast to CO$_2$ which increased slightly. The same trend was observed for the gasification of wood by Jeanmart et al$^{11}$ This fact is explained by the excessive combustion of the char in the pyrolysis stage when the AR is high since more air was injected in the pyrolyzer. In this case, we suppose that the produced char during the pyrolysis stage is consumed more than need. Thus, we consider an overconsumption of char during the pyrolysis stage. The opposite trend is observed for H$_2$ and CH$_4$ which increased when a larger amount of air was injected into the pyrolysis zone (ie, increased of AR). The increase of methane fraction with AR may be related to the degradation of PE in the pyrolysis stage. The plastic complete degradation achieved when AR is high lead to the increase of methane production at the pyrolysis stage since PE promote the production of CH$_4$, CO, CO$_2$ and H$_2$O during its co-pyrolysis with biomass.$^{18}$ It important to note that the increase of steam in the pyrolysis state, resulting from PE decomposition explained the increase of hydrogen in the produced gas due to the shift reaction promotion by the steam. However, the injection of a significant amount of air into the pyrolysis zone (AR = 0.49) leads to a decrease in the volume fractions of H$_2$ and CH$_4$ in addition to CO due probably to the temperature drop in the reduction zone as shown by Table 3.

H$_2$ and CH$_4$ reached their maximum values at the intermediate air ratio of 0.43. As a consequence the maximum values of LHV of the gas, energy and carbon conversion efficiencies of the co-gasification were achieved for the intermediate air ratio of 0.43. Thus, the best composition of the gas was obtained for the AR of 0.43 for the co-gasification of wood and 20% (in mass) of polyethylene.

### Table 3 Operating parameters for the co-gasification tests

| Characteristic       | Test 1   | Test 2   | Test 3   |
|----------------------|----------|----------|----------|
| AR                   | 0.35     | 0.43     | 0.49     |
| Mean temperature in different zones (°C) |          |          |          |
| Pyrolysis zone       | 293      | 286      | 351      |
| Oxidation zone       | 985      | 900      | 929      |
| Reduction zone       | 683      | 772      | 636      |
| Operating parameters |          |          |          |
| ER                   | 0.31     | 0.31     | 0.33     |
| Total flow (m$^3$/h) | 54.5     | 57.2     | 60.85    |
| $V_{N_{\text{gas}}}$ (Nm$^3$/h) | 68.50    | 74.05    | 74.02    |
| $m_{\text{fuel}}$ (kg/h) | 27.12    | 28.24    | 29.00    |
| $Y_{\text{gas}}$ (Nm$^3$/kg) | 2.53     | 2.62     | 2.55     |

### FIGURE 5

Fluctuations of air flow during the co-gasification trial: $d_{\text{pyro}}$, $d_{\text{oxyd}}$, and $d_{\text{total}}$ for the flow in the pyrolysis zone, oxidation zone, and the total flow, respectively.

### FIGURE 6

The average temperature within the pyrolysis from the top to down at the different air ratio.
### 3.2 Mass, elemental, and energy balances

The proximate analysis of PE and residues of the co-gasification are presented in Table 5. Ash presence in PE is due to the impurities and additives in the plastic waste. The results were integrated in the calculation of the different balances considered in the present study.

The balances of mass, chemical elements, and energy during the co-gasification of wood and PE at the optimized AR are summarized in Table 6. The balances were reported over a period of one hour. The differences were expressed as a percentage of the inputs mass and energy.

The mass balance was completed with satisfying accuracy. The difference between the input and output mass of nitrogen in the elemental balance was due to the measurements uncertainties since the nitrogen was not transformed in the process. The other chemical elements balance revealed a maximum gap of −7% obtained for carbon. This difference shows an overestimation of the mass of carbon in the co-gasification products. Indeed, in this study, the amount of fixed carbon (70%) and volatiles (4%) in the residues was assimilated to carbon. Thus, the hydrogen and oxygen content in the residues were not taken into account in their respective mass. This contributed to the gap of 3.24% and 2.38% obtained for mass balance of hydrogen and oxygen, respectively. However, the differences obtained in the elementary balance are acceptable due to the uncertainties of measurements.

The heat balance showed a significant energy gap of 12% of the input energy. This energy gap can be assimilated to the energy lost through the reactor walls. Jayah had shown that energy loss through the reactor walls can achieve 12% of the input energy in the downdraft gasifier. In addition, the light hydrocarbons (C2H2, C2H4, and C2H6) and tar content, which were not measured in the present study, had contributed to the energy gap despite their low proportion in the produced gas. Indeed, the volume fractions of light hydrocarbon compounds in the range of 0.7% to 1.7% were reported during the co-gasification of biomass and polyethylene. Concerning tar content, maximum average fraction of 240 mg/Nm3 was reported by previous tests in the gasifier.

The energy lost in the residues is particularly high as a consequence of the mass and high carbon content of the residues. Note that the sum of losses \( (E_r + E_v + E_{gap}) \) is higher than the losses reported by Martinez et al. Thus, the conversion of the biomass during the co-gasification of wood and PE may be lower than the conversion of biomass achieved for the gasification of biomass alone.

### Table 4

| Composition | Test 1 | Test 2 | Test 3 |
|-------------|--------|--------|--------|
| AR          | 0.35   | 0.43   | 0.49   |
| CO (%v)     | 17.27  | 15.66  | 13.54  |
| CO2 (%v)    | 10.77  | 10.49  | 11.85  |
| CH4 (%v)    | 0.86   | 2.23   | 1.79   |
| H2 (%v)     | 15.41  | 17.64  | 14.83  |
| N2 (%v)     | 55.69  | 53.98  | 58.0   |
| LHV (kJ/Nm³)| 4147.85| 4674.48| 3945.06|
| \( \eta_\text{gas} \) (%) | 54.88  | 64.35  | 52.75  |
| \( \eta_\text{carbon} \) (%) | 73.09  | 74.52  | 69.74  |
3.3 | Analysis of the impact of PE

The comparison of the co-gasification of wood and 20% of PE and the gasification of wood only in the NOTAR® two-stage gasifier is shown in Table 7. The equivalence ratio obtained for the gasification of the mixture of wood and PE and of wood, in the optimum conditions, was similar despite the difference of feedstock flow due to the self-adjustment of the gasifier as said before. An improvement of gas yield ($Y_{\text{gas}}$) was achieved by co-gasification of wood and PE due to complete degradation of PE during the co-gasification of PE and wood as reported in the literature.\textsuperscript{3,6}

Indeed, in the temperature range of the pyrolysis zone (500-550°C) of the present study, PE and wood mixture underwent a complete degradation into a major part of gas yield and low fraction of char due to the polyethylene total volatilization.

In order to optimize the energy efficiency, the injection of less air in the pyrolyzer is need for the co-gasification of mixture of wood and PE comparatively of wood gasification. This is supported by the low AR needed for the co-gasification of PE and wood comparatively to the wood gasification (Table 7). Noted that the high quantity of produced gas at the pyrolysis stage is mainly composed of CH\textsubscript{4} and light hydrocarbon compound (ethylene), CO, and CO\textsubscript{2}.\textsuperscript{21} This means that more oxygen is needed to oxidize the gas from the co-pyrolysis comparatively to the case of wood gasification. Furthermore, the pyrolysis air reacts principally with wood since PE mostly undergoes thermal degradation as said before. Thus, air volume used for pyrolysis during co-gasification of wood and PE mixture must be lower than its volume for wood only pyrolysis.

The gas from the pyrolysis zone will be partially oxidized in CO, CO\textsubscript{2}, and H\textsubscript{2}O before to enter in the reduction zone. The following reactions are involved in the reduction zone:

\begin{align*}
\text{(R1)} & \quad \text{C} + \text{CO}_2 & \leftrightarrow 2\text{CO} & \quad \text{Boudouard reaction} \\
\text{(R2)} & \quad \text{C} + \text{H}_2\text{O} & \leftrightarrow \text{CO} + \text{H}_2 & \quad \text{Char steam gasification} \\
\text{(R3)} & \quad \text{C} + 2\text{H}_2 & \leftrightarrow \text{CH}_4 & \quad \text{Methanation reaction} \\
\text{(R4)} & \quad \text{CO} + \text{H}_2\text{O} & \leftrightarrow \text{CO}_2 + \text{H}_2 & \quad \text{Water gas shift reaction} \\
\text{(R5)} & \quad \text{CH}_4 + \text{H}_2\text{O} & \leftrightarrow \text{CO} + 3\text{H}_2 & \quad \text{Steam reforming reaction(R5)}
\end{align*}

The results show lower performances (energy efficiency and LHV of the produced gas) of co-gasification of wood and PE than those of biomass gasification. Many factors can explain the lower performances of wood and PE co-gasification.
Firstly, the reactivity of the char produced during the pyrolysis of biomass plays a key role for the reaction process in the reduction zone. However, there is not enough information about the impact of PE on the derived char properties contrarily to gas and liquid phases. A synergetic effect on gas, liquid, and char fraction has been reported during the co-pyrolysis of biomass and PE.\textsuperscript{18,22-24} Xue et al\textsuperscript{23} had notified a considerable decrease in the reactivity of the char derived from biomass co-pyrolysis with PE. The presence of PE reduced the reactive surface and block the char pores.\textsuperscript{23} However, according to Honggang et al,\textsuperscript{18} the char structure is not affected during the co-pyrolysis of biomass and PE. One can suppose that an incomplete decomposition of PE during the co-pyrolysis may block the char pores and reduce its reactivity as said by Xue et al.\textsuperscript{23}

Second, a fraction of biomass char reacts with the gas phase produced by PE volatilization during the pyrolysis state as suggested by Déparois et al.\textsuperscript{19} This may be explained by the low carbon content of the char produced by the co-pyrolysis comparatively to biomass pyrolysis. Indeed, Honggang et al\textsuperscript{18} had shown a considerable loss of carbon content of the char produced by co-pyrolysis of PE and biomass comparatively to biomass alone pyrolysis. Thus, the char conversion through the Boudouard reaction, the char steam gasification, and the methanation reactions are limited due to the char low carbon content and low reactivity during the reduction step. This is supported by the considerable unconverted residues masses which content high fixed carbon content of 70\% against 45\% for wood gasification residues obtained by Berger.\textsuperscript{25}

In addition to the low char reactivity and carbon content at the reduction bed, the relatively low temperature which prevailed in the reduction zone (~772°C) will decrease the kinetic of these reactions. The acceleration of the Boudouard and the char steam gasification require a temperature range of 830-900°C.\textsuperscript{3} The limitation of Boudouard and char steam gasification reactions is the main reason of CO decrease during the co-gasification of PE and wood comparatively to wood gasification since these reactions are the principal’s ways of CO production during the gasification process. Regarding the temperature in the reduction zone (772°C), the water gas shift reaction may be predominant in the gasification process.\textsuperscript{3} Although the water gas shift reaction may be favored by prevailed reduction temperature and PE promotes steam production during pyrolysis step, H2O fraction is particularly low since the used wood is dry (10\% humidity) and there is not steam injection. This fact can reduce the CO\textsubscript{2} and H\textsubscript{2} production through the water gas shift reaction. The hypothesis agrees with the lower CO\textsubscript{2} and H\textsubscript{2} obtained for the co-gasification of PE and wood comparatively to wood gasification (Table 7). The steam injection in the reduction zone may have an advantage in the co-gasification of PE and wood in order to improve the carbon conversion and the H\textsubscript{2} and CO by the water gas shift reaction and the char steam gasification.

| Feedstock | Fuel (kg/h) | ER | LHV (kJ/Nm\textsuperscript{3}) | LHV (kJ/Nm\textsuperscript{3}) | CO\textsubscript{2} (%) | CH\textsubscript{4} (%) | H\textsubscript{2} (%) | CO (%) | CH\textsubscript{4} (%) |
|-----------|-------------|----|-------------------------------|-------------------------------|-------------------------|-------------------------|-------------------------|---------|-------------------------|
| Wood + PE (Present study) | 0.43 | 0.31 | 4674 | 64.35 | 64.35 | 2.62 | 15.66 | 2.23 | 17.64 |
| Wood\textsuperscript{25} | 0.61 | 0.29 | 4820.3 | 73 | 73 | 2.45 | 19.77 | 12.49 |
Considerable increase of CH₄ was found for PE and wood co-gasification. Bacaicoa-García et al.⁶ have associated the improvement of CH₄ fraction to PE cracking instead of methanation reaction, since the temperature achieved in the reduction zone and the low pressure (1 bar) are not favorable to methanation reaction. Thus, the thermal cracking of the PE explains the presence of considerable CH₄ and light hydrocarbon in the gas produced by the co-gasification of wood and PE as reported in the literature.⁶ LHV and the energetic efficiency of the co-gasification of PE and wood achieved in the present study are comparable to those obtained for the gasification of wood, thanks to the considerable fraction of CH₄. The energetic performances may be even higher if the lighter hydrocarbon had been measured in the present study.

4 | CONCLUSION

The fuel composed of 80% wood and 20% polyethylene was successfully gasified using a co-current and two-stage type of gasifier. A pyrolysis peak temperature of 550°C and the highest reduction average temperature of 772°C were obtained when an intermediate air ratio of 0.43 is used for the co-gasification. Thus, complete degradation of PE in the pyrolyzer and maximum char gasification rate in the reduction zone are reached for the intermediate air ratio. The gas composition was also affected by air ratio and PE addition in the feedstock. CO decreases with the air ratio, like in the case of the gasification of wood in a two-stage gasifier. High AR lead to an overconsumption of char and a low reduction temperature and a decrease of CO content in the produced gas. H₂ and CH₄ volume fractions present a peak for the intermediate air ratio of 0.43. The results showed an optimal value of 4674 kJ.Nm⁻³ and 64.35% of LHV and energy efficiency, respectively, achieved for the air ratio of 0.43. Thus, the optimization of the co-gasification performances was achieved for the intermediate air ratio of 0.43 with the gas composition of 15.66%, 17.64%, and 2.23% for the volume fraction of CO, H₂, and CH₄, respectively. However, polyethylene caused a sensible decrease of gas LHV and the co-gasification energy efficiency due to the char low reactivity and low carbon content comparatively to wood gasification. The analysis shows the probable advantage of steam injection in the reduction zone in order to increase H₂ and CO in the produced gas.

Nomenclature

| Symbol | Definition |
|--------|------------|
| L      | Latent heat of condensation (kJ/kg) |
| LHV    | Low heating value (MJ/m³ or MJ/kg) |
| M      | Molar mass (g/mol) |
| m      | Mass (kg) |
| m_fuel/sec | Average mass of one sequence of fuel feeding (kg) |
| m_water | Mass of the water vapor in the air (kg) |
| n      | Molar fraction of the gas species (mol/mol) |
| N_seq  | Number of sequences of feeding |
| R      | Ideal gas constant (J mol⁻¹ K⁻¹) |
| T      | Gas temperature (K) |
| T₀     | Normal temperature (273.15 K) |
| T_a    | Ambient temperature (K) |
| t_ash  | Ash content of the biomass (%) |
| th     | Humidity content of biomass (%) |
| P_a    | Atmospheric pressure (1.013 bar) |
| V      | Volume (m³) |
| Vm     | Molar volume (m³/mol) |
| VN     | Normal volume (Nm³) |
| w_sat | Humidity ratio of air (kg/kg of dry air) |
| η_carbon | Carbon conversion efficiency |
| η_gas  | Gasification energy efficiency |
| ρ(T)   | Density at temperature T (kg/m³) |
| %      | Mass percentage of chemical element C, H, O, and N |
| VN     | Normal volume (Nm³) |

Subscripts

| subscript | Definition |
|-----------|------------|
| air       | Air |
| ash       | Ash |
| b         | Biomass (Wood) |
| carbon    | Carbon |
| Fuel      | Mixture of wood and polyethylene |
| gas       | Gas |
| i         | Gas species i, (CO, CO₂, H₂, CH₄, N₂, O₂) |
| in        | Input products in the reactor |
| out       | Output products of the reactor |
| PE        | Polyethylene |
| r         | Residues |
| v         | Water vapor |
| water     | Liquid water |

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