Thermodynamic study of residual biomass gasification with air and steam

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Abstract: This paper presents the results obtained from modeling the gasification process of residual biomass, based on the non-stoichiometric Gibbs-free-energy minimization method. The RAND algorithm (Li, 2002) was used for the calculation of thermodynamic equilibrium and implemented in a computational tool. 44 chemical species were taken into account, 42 of them in the gas phase and two more in the solid phase (carbon and sulfur). The model offers good results for the conditions tested and allowed the selection of air, steam, or a combination of those, as gasification agent. The results obtained for a fixed biomass composition and operating conditions of 740°C and 1 bar with variation of the gasification medium composition were analyzed. It was possible to determine the maximum theoretical yield and other process thermodynamic limitations. An analysis of the deviations presented between experimental results reported in literature and those obtained from the equilibrium model was also carried out. The model implemented in this work is a useful tool for the analysis of the gasification process. The detailed assessment of the influence of temperature and composition of the biomass on gasification is being currently performed.

Keywords: RAND algorithm, residual biomass, gasification, equilibrium model, gasification agent.

1. Introduction

In Colombia, the most common thermochemical transformation process for energy use of biomass is combustion (direct or with cogeneration), especially in non-interconnected areas (García *et al.*, 2014; Silva and Nakata, 2009). However, combustion of solid biomass in traditional boilers and stoves has low efficiency and generates environmental and health problems due to the release of particulate matter and unburned hydrocarbons (Baratieri *et al.*, 2008). In gasification, as an alternative process to combustion, a syngas is produced which, once cleaned, can be used directly in production of thermal energy or in electric power generation by combustion. This process generates lower emissions of SO_2, CO_2 and particulate matter (Schuster *et al.*, 2001), thus avoiding the negative environmental impact of energy use of biomass by combustion. The syngas can also be used as raw material for production of liquid fuels, pure hydrogen and synthetic natural gas, among other products of high added value (Pröll and Hofbauer, 2008). These favorable characteristics make the biomass gasification a process worth being evaluated in detail.

Biomass gasification is a complex process, involving multiple factors, such as type and amount of gasification agent, composition and moisture content of biomass, type of reactor, reaction conditions, etc. A good understanding of the influence of these factors is needed to facilitate the design of any type of gasifier (Hosseini *et al.*, 2012). The thermodynamic equilibrium model is a useful approach to develop such an understanding. Even though the composition of the product gas determined by such model can only be considered as indicative since the equilibrium conditions are seldom reached in real gasifiers (Basu, 2006), it is suitable for estimating the maximum theoretical yield of the process, and for providing a preliminary view of its behavior (according to the thermodynamic principles that could limit it) (Ferran, 2013; Li, 2002).

The models based on thermodynamic equilibrium have been widely used because, unlike kinetic models, they can be easily applied to any type of gasifier and do not require a large number of previous experimental data for its implementation in a computational tool (Schuster *et al.*, 2001). Also, in a kinetic model, the complexity increases significantly when a large number of chemical species is considered because the design parameters of the reactor (such as species composition profile and gas residence time) should be included, while the equilibrium model omits them.

There are two methods to find equilibrium concentrations of the products obtained during a chemical transformation process: stoichiometric and non-stoichiometric. Both are based on the minimization of the Gibbs-free-energy function of the thermodynamic system under study, but differ in how it is found (Ferran, 2013). In the present study, the non-stoichiometric method was chosen for modeling the gasification process. Unlike the stoichiometric method, for the non-stoichiometric, knowing the stoichiometric equations and the equilibrium constants of the reactions involved is not necessary (Smith and Missen, 1982). In addition, the use of Lagrangian multipliers facilitates the implementation of the non-stoichiometric method in computational programs (Smith *et al.*, 1996) without oversimplifying the thermodynamic system, which is often the case of the stoichiometric method when a small number of reactions is chosen. Such oversimplification may lead to finding a local minimum of the Gibbs function instead the global minimum (Li, 2002). Since the computational implementation of the non-stoichiometric method is simpler, it allows the consideration of many more chemical species involved in the gasification than the stoichiometric method, thus guaranteeing that the global minimum of the Gibbs function is found.

The present study considers the participation of 44 chemical species (42 in gas phase and carbon and sulfur in solid phase) and 5 constituent elements (C, H, O, N and S, as determined in the ultimate analysis of biomass). A theoretical analysis of the results is proposed, from the point of view of chemical equilibrium, for the gasification process with air and steam, as well as with combinations of those. The most favorable operation conditions for the gasification of residual biomass with different gasification agent compositions are estimated. Also, a validation of the model was carried out comparing the results with experimental data reported in literature.

2. Methodology

2.1 Original program and enhancements

RAND, Brinkley and NASA are the most used algorithms for solving the equilibrium problem using non-stoichiometric formulation (Smith and Missen, 1982). The RAND algorithm was implemented in the present study and the computational tool Matlab® was selected for its implementation. Details of the basic structure of the method are available in literature (Li, 2002; Smith and Missen, 1982).

The implementation of the RAND algorithm was carried out based on the codes reported by Li (2002) and Sakaguchi (2010), who studied fluidized bed gasifiers experimentally and theoretically. The code was designed for a biomass mass flow of 1 kg/h on as received basis (ar). The input variables required for the program execution are: gasification temperature and pressure; equivalence ratio (ER), calculated as the ratio between the moles of air fed to the gasifier and the stoichiometric moles of air required for total combustion of the biomass (in the case of air gasification); steam to carbon ratio (SC), defined as the ratio between the moles of steam fed to the gasifier and the carbon moles present in the biomass (for steam gasification); the ultimate analysis of the biomass on dry basis (db), its moisture content on ar basis, M_{ar}; and the temperatures of biomass, air and/or saturated steam entering the gasifier. In this study such temperatures were fixed in 25 °C, 300 °C and 150 °C respectively (conditions reported in literature (Li, 2002)).

When specifying in the program C, H, O, N and S as the constituent elements of the process, the algorithm charges the thermodynamic properties of all 44 species shown in table 1 (all of these species are also considered by Li (2002)), which containing at least one of the five chemical elements mentioned. Some of these species are unstable radicals (CH, OH, NH among others) which aid the convergence of the algorithm, since many of the gasification final products can be formed from these radicals in spontaneous intermediate reactions (and there is no total certainty of how such intermediate reactions occur). The output variables are: the equilibrium composition of the product gas, the gas heating value and its volume flow, the efficiency of the gasification, the amount of solid carbon generated (species no. 43 in table 1), and the energy required for the process determined by the energy balance around the gasification reactor. The dimensional variables are given per kg of biomass on ar basis. Chars and tars formation are not included in the equilibrium model used here.

Table 1. Chemical species considered in the equilibrium model (Adapted from Li (2002))

Species formula

1. C	12. O	23. NCO	34. S_2
2. CH	13. O_2	24. NH	35. SO
3. CH_2	14. CO	25. NH_2	36. SO_2
4. CH_3	15. CO_2	26. NH_3	37. SO_3
5. CH_4	16. OH	27. N_2O	38. COS
6. C_2H_2	17. H_2O	28. NO	39. CS
7. C_2H_4	18. H_2O_2	29. NO_2	40. CS_2
8. C_2H_6	19. HCO	30. CN	41. HS
9. C_3H_8	20. HO_2	31. HCN	42. H_2S
10. H	21. N	32. HCNO	43. C(s)
11. H_2	22. N_2	33. S	44. S(s)

2.2. Efficiency of gasification

The efficiency of the gasification process (in equilibrium conditions) was determined as the ratio between the energy produced and the energy supplied to the gasifier, as follows:

$$\eta(\%) = \frac{V_{dry\,gas}LHV_{gas}}{m_{fuel}LHV_{fuel\,db} + (\dot{Q}_{req},\ si\ \dot{Q}_{req} > 0)} \quad (1)$$

Where LHV_{gas} is the lower heating value of the product gas (given in kJ/Nm^3 at 298 K and 1 atm), calculated as the sum of lower heating values of the combustible components in the mixture (species 5, 6, 7, 8, 9, 11, 14, 38, 40 and 42 of table 1) multiplied by the corresponding volumetric fractions; $V_{dry\,gas}$ is the volume of the dry product gas (given in Nm^3/kg of biomass as received, ar) calculated using the ideal gas law; $LHV_{fuel,db}$ is the lower heating value of biomass on dry basis (in kJ/kg); m_{fuel} is the mass flow of biomass (in kg/h); and $\dot{Q}_{req}$ is the heat being supplied or removed from the process to maintain operation at constant temperature (in kJ/kg·h of biomass as received) calculated from the energy balance for the gasifier. If $\dot{Q}_{req}$ is less than zero, it does not add to the denominator of equation (1). Table 1 lists the species under consideration, species 1 to 42 are in gas phase and species 43 and 44 are in solid phase.

The code implemented in this study solves some inconsistencies of Sakaguchi's original code related to the determination of biomass enthalpy of formation in ar basis. These inconsistences of the code consisted in using the wrong basis for biomass (db instead of ar basis) and in including the amount of steam supplied as gasification agent in the calculation of enthalpy of formation of the biomass. Sakaguchi's code assumes the temperature of the biomass moisture equal to that of the steam used for the gasification; in this study such temperature is taken equal to that of the biomass (25 °C), considering that moisture enters the gasifier in the liquid phase. Once the code was implemented, it was validated by comparing the gas composition reported in the studies of Li (2002) and Baratieri (2008) for gasification in thermodynamic equilibrium with those calculated in this study under the same conditions. Good agreement was found.

In the present work, the composition of a reference biomass was used. The ultimate composition of a mixture of sawdust from different types of woods on dry basis reported by Li (2002) as "typical sawdust" was chosen (C: 50.88%, H: 6.60%,

O: 40.53%, N: 0.51%, S: 0.34%, Ash: 1.14%). The operating reference conditions are 1 bar and 740°C (also used by Li (2002) in his experiments).

3. Results and discussion

The gasification process was simulated for different gasification agent compositions. The effect of varying the equivalence ratio (ER) and the steam to carbon ratio (SC) was analyzed. The product gas data are presented for dry gas (except the molar percentage of water which is based on the wet gas), unless otherwise specified.

On the left hand side of figure 1, the concentrations of the product gas (fig. 1(a)), and the behavior of the lower heating value (fig. 1(b)) , as well as the efficiency (fig. 1(c)) and the energy required by the process (fig 1(d)), are shown as a function of the equivalence ratio. In the case of air gasification without the presence of steam (SC = 0), at low equivalence ratios reduced species such as H_2, CO and CH_4 (which require little or no oxygen for their formation) predominate, and the fraction of unconverted solid carbon is high (14.7 % for ER = 0.1, 740 °C, 1 bar and M_{ar} = 0%). This is due to the low amount of gasification agent available to react with the carbon present in the biomass. Low ERs produce low gas volumes with higher heating values, while higher ERs favor the total conversion of biomass, generating high volumes of a gas with low heating values. Low heating values are caused by the increase of N_2 coming from the excess air, as well as by the promotion of combustion reactions instead of gasification reactions when availability of O_2 in the system is high (producing more H_2O and CO_2 instead of H_2 and CO), according to Le Chatelier's principle. For air gasification, a maximum efficiency is observed at ER=0.3 (M_{ar} = 0%, 740 °C and 1 bar) according to figure 1(c), such value is within the ER range suggested by Li (2002) of 0.3 to 0.35 to maximize the efficiency of experimental gasification. At these conditions, there is a balance between two effects that appear when increasing the equivalence ratio: decrease in gas heating value and decrease of the process energy requirement.

With a biomass moisture content of 20 % ar, the maximum efficiency of air gasification decreases (fig. 1(c)) because of the substantial increase in the heat that must be supplied to the process for the evaporation of moisture. The moisture content also causes a shift of the maximum efficiency towards a lower equivalence ratio, because the moisture can act as an auxiliary gasification agent once vaporized, which is useful to increase the conversion of carbon at low equivalence ratios. Thus, the equilibrium model showed a reduction in the percentage of unconverted solid carbon from 14.7 % in absence of moisture to 1.9 % for M_{ar} =20 % and the same operating conditions (740 °C, 1 bar and ER = 0.1).

In the case of steam gasification without the presence of air (ER=0), a gas of low heating value is produced as the steam to vapor ratio (SC) and the moisture content in the biomass increase (figure 1(f)). This is due to the increase in the concentration of unreacted water in the product gas and consequent decrease in the concentration of species with high heating value. According to figure 1(g), the maximum efficiency in steam gasification is obtained at SC = 0.6 approximately (for dry biomass). Although it is possible to obtain high lower heating values in the product gas (LHV_{gas}) and a reduction in the amount of the heat requirement at lower SCs, a high percentage

of unconverted solid carbon is generated (e.g. 4.4 % of the total moles generated at SC = 0.5, 740 °C, 1 bar and dry biomass). With SC ratios above 0.6 carbon present in biomass is fully gasified but the LHV_{gas} decreases and the heat requirement increases, causing a decrease in process efficiency. In steam gasification, LHV_{gas} does not fall to zero with high gasification agent flows, because total combustion reactions that generate species of null heating values (H_2O and CO_2) are not favored.

In order to analyze the gasification process using the combination of air and steam as gasification agent, the SC ratio was set at 1.0 and the equivalence ratio was varied. The SC ratio was chosen between 2.1 (recommended by Sakaguchi (2010)) and 0.6, for which the maximum efficiency of steam gasification was obtained in this study. It is observed in figure 1(c) that the feed of steam causes a decrease in the efficiency of air gasification and even the maximum of the curve when SC and M_{ar} are equal to 0 disappears. This is due to the increase in the progress of the water-gas shift reaction, which consumes CO (of LHV slightly higher than that of H_2; 283 kJ/mol and 242 kJ/mol respectively (Waldheim and Nilsson, 2001). The same phenomenon occurs in the presence of moisture in biomass, but for 20% ar the decrease in gas lower heating value is not significant. For ERs greater than 0.4, the rapid decrease in efficiency is not due to the water-gas shift reaction, but rather to the high feasibility of the combustion reactions producing CO_2 and H_2O (regardless of the presence of steam). At those conditions, LHV_{gas} are similar for both, gasification with air and with air-steam combinations.

At ERs greater than 0.15, the efficiency of the gasification with the air-steam mixture (and 0 % moisture in biomass) is lower than for air gasification. This is due to the increase of the water concentration in the product gas (figure 1(a)) and to the increase in the process heat requirement (fig. 1(d)). The presence of steam in the system favors endothermic reactions such as methane steam reforming, but for equivalence ratios lower than 0.15, steam also promotes the solid carbon conversion to CO and H_2 in an extent that the efficiency is improved in comparison to the gasification in the absence of steam and biomass moisture. Figure 1(d) shows that the ER at which the heat required by the process (Q_{req}) is null increases as the presence of water (either from biomass moisture or gasification agent) increases. This is due to the aforementioned promotion of endothermic reactions in which water participates. At higher ER, exothermic reactions predominate and therefore heat is released from the gasifier ($Q_{req} < 0$) and in this case, it is necessary to remove such heat to maintain the operating temperature constant.

The results obtained from the model keeping fixed the ER in 0.2 and 0.3 and varying the SC ratio are shown on the right hand side of figure 1. ERs of 0.2 and 0.3 are used taking into account the maximum efficiency observed around of these values (fig. 1(c) for SC=0 and M_{ar} = 0 and 20%). When air is introduced in steam gasification (and 0% of biomass moisture), the efficiency decreases due to the increase in the N_2 concentration and to the presence of O_2, which favors the combustion reactions. However, the introduction of air helps reducing the high energy consumption of the steam gasification, which increases significantly with the increase of the SC ratio (fig. 1(h)).
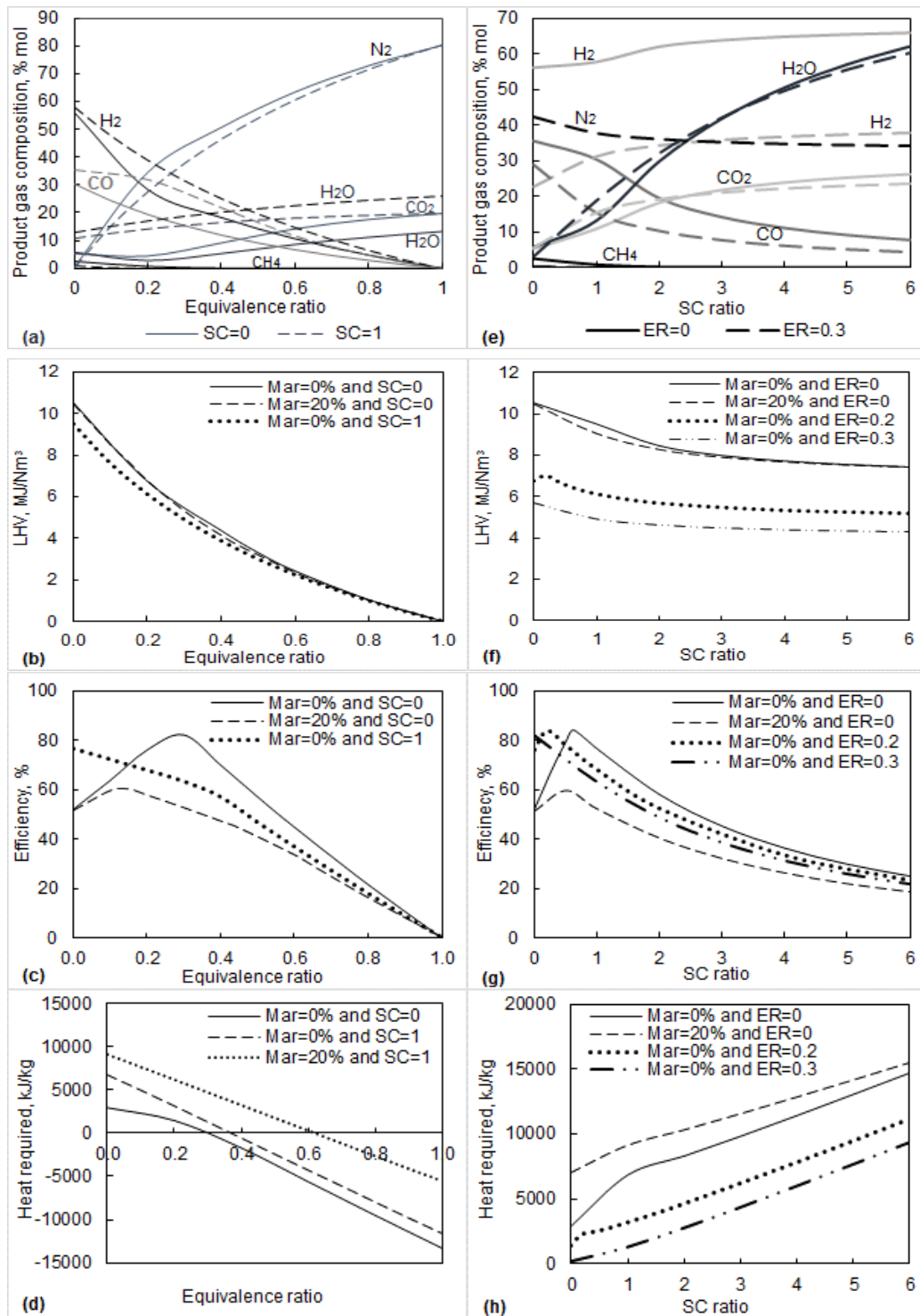
Figure 1. (a) and (e) composition of the dry product gas from gasification of dry biomass, (b) and (f) dry gas lower heating value, (c) and (g) gasification efficiency and (d) and (h) heat required by the process, as a function of the equivalence ratio (ER) for different biomass moistures and different steam to carbon ratios (left side) and of the steam to carbon ratio (SC) for different biomass moistures and different equivalence ratios (right side). Reference biomass, P=1 bar, T=740°C.

For ER = 0.2 and SC ratios lower than 0.8, the gasification efficiency is greater than that obtained using only steam. This is because the partial and total oxidation reactions promoted by the O_2 (from air) release heat that can be consumed by endothermic gasification reactions; which reduces the energy requirement and increases the efficiency of the process (the same happens when using ER = 0.3 and SC ratios lower than 0.6). For the conditions of air-steam combination studied here, a maximum efficiency of 83.8 % was observed at a SC = 0.2, ER = 0.2 and M_{ar} =0 %, slightly lower than the maximum presented in the steam gasification (84.1 % for SC = 0.6).

From the above analysis it can be said that only small amounts of steam are recommended to be added during air gasification to promote carbon conversion and increase the process efficiency. Higher steam proportions generate more energy expenditure and greater dilution of the species of high heating values present in the product gas, which contributes to decrease the efficiency. Using ER = 0.3 there is sufficient oxygen available in the system and the addition of steam becomes unnecessary. For non-

equilibrium conditions, the amount of remaining solid carbon is usually greater than that predicted by the model due to limitations of different types (Li, 2002), therefore, at equivalence ratios of 0.3 or higher the addition of steam may be required to increase carbon conversion and increase process efficiency. The lower the air equivalence ratio the larger the amount of steam required to convert the remaining solid carbon, so for ER = 0.05 a SC ratio of 0.5 is required to increase the efficiency from 57.9 % to 85.5 %. This efficiency is higher than the maximum observed for gasification carried out only with air or only with steam (84.1 % and 82.3 % respectively at 740°C, 1 bar and 0 % moisture).

3.1. Comparison between equilibrium model and experimental data

In order to analyze the deviations of the equilibrium model estimations with respect to experimental data reported in literature, the measurements of composition, yield (volume) and lower heating value of the product gas obtained by Brambilla (2014) in a laboratory scale bubbling fluidized bed gasifier for sewage sludge, (whose ultimate analysis in dry basis is: C: 27.3 %, H: 4.8%, O: 18.9%, N: 4.1%, S: 0.9%, ash: 44.0%, moisture: 7% ar) were compared with the results obtained by the model. The same process conditions as in the experiment were used for modelling. The measurements reported in Brambilla (2014) were chosen because the variations of equivalence ratios and steam to biomass ratios (defined as the relation between the steam and the dry ash free biomass mass flows feeding the reactor) were made keeping the other operating conditions constant, unlike other studies reviewed.

In figure 2 a comparison between the experimental and calculated values of product gas composition, low heating value and yield are presented. A clear deviation between

measurements and model estimations is observed. This is due to the influence of kinetic, hydrodynamic, and mass and heat transfer phenomena that are not considered in the equilibrium model. However, the differences between product gas concentrations predicted by the model and measured experimentally become lower as the equivalence ratio increases, because of the predominance of the combustion reactions at high air supplies. Combustion reactions tent to achieve thermodynamic equilibrium faster than the gasification reactions due to its higher reaction rates (Basu, 2013). This causes a reduction in the residence time required for oxidation of the solid (char) and gaseous (H_2, CO, CH_4, tars, etc.) fuels inside the gasifier. The increase in the air flow feed to the gasifier also favors the chars and tars consumption in combustion reactions, whose main products (CO, CO_2 and H_2O) are considered in the thermodynamic equilibrium model, unlike chars and tars. This reduces the deviation in mass balance estimated by the model, taking into account that such deviation is proportional to the amount of char and tar produced during the operation of a real gasifier. Because of the same reason, the heating value and yield of the product gas estimated by the equilibrium model are also closer to the experimental values as the equivalence ratio increases, as shown in figure 2(b).

Regarding the composition of the product gas resulting from the gasification with air-steam mixtures, according to figure 2(c), it is clear that the experimental concentrations of CO_2 and CO are not very sensitive to the increase in SB ratio compared to that estimated by the model, possibly due to the predominance of total combustion reactions in the bubbling bed gasifier over other reactions such as the water-gas shift reaction, observed in presence of air at an equivalence ratio of 0.3. This also explains the slightly
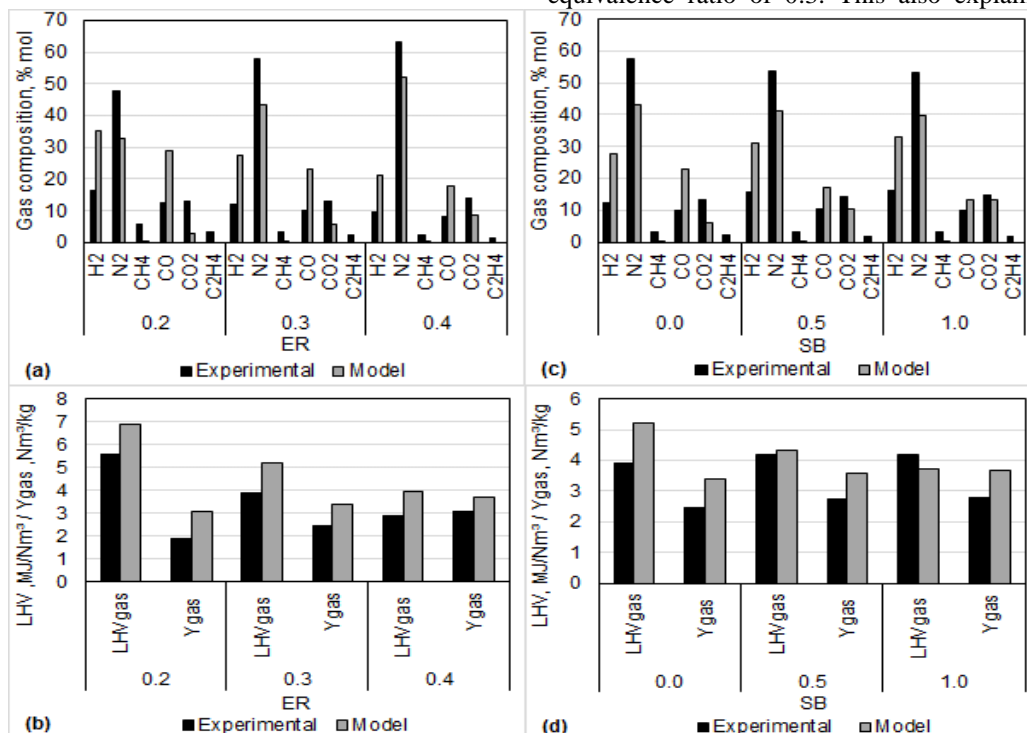

Figure 2. Comparison between: (a) and (c) the molar composition, (b) and (d) the lower heating value (LHVgas) and dry product gas yield (Ygas), calculated by the equilibrium model and measured by Brambilla (2014) in a bubbling fluidized bed gasifier for sewage sludge at different equivalence ratios and SB = 0 (right side) and at different steam to biomass ratios (SB) and ER = 0.3 (right side). T = 850 ° C, P = 1 atm.

increase in experimental concentration of H_2 with the rise of SB ratio while according to the model, such increase is considerable.

Figure 2(c) also shows that the differences between the experimental and calculated concentrations of CO and CO_2 in the product gas are lower as the steam to biomass ratio increases. According to the equilibrium model, the water-gas shift reaction causes a decrease in the CO concentration in the product gas to values relatively close to those measured experimentally, which are always lower than those estimated by the model. This occurs because the formation of char and tar causes a decrease in the amount of carbon (from the biomass) available for production of gaseous species such as CO. Similarly, due to the water-gas shift reaction, the model estimates an increase in the CO_2 concentration (as the SB ratio rises) to values close to those obtained experimentally, which are always higher than those calculated by the model (figure 2(c)) because of the prevalence of total combustion reactions over gasification reactions.

On the other hand, experimental measurements show that methane and ethylene consumption are promoted at high steam to biomass ratios (probably by reforming reactions), their concentrations get therefore closer to those calculated by the equilibrium model (figure 2(c)). The model estimates lower methane and ethylene concentrations because these are usually intermediate products of chars and tars decomposition, but at thermodynamic equilibrium it is assumed that time for these hydrocarbons to decompose is sufficient. Such increase in the conversion of chars and tars into light hydrocarbons increases the product gas heating value, whereas the equilibrium model predicts the opposite. Because of this, the heating values of the product gas measured experimentally and calculated by the model are only similar at a SB ratio of 0.5 as shown in figure 2(d).

The model predicts gas volume yields higher than those measured experimentally, because it assumes that the whole biomass is gasified and does not take into account the biomass fraction that is usually converted into chars and tars in experimental gasification.

Although the difference between the equilibrium model predictions and the experimental measurements is evident, it is worth highlighting that the trends of molar percentages of the main species in product gas estimated by the model are the same as those observed experimentally for the bubbling bed gasifier (figures 2(a) y (c)). This confirms the utility of thermodynamic equilibrium model in understanding the operation of a real gasifier, even though it rarely reaches such equilibrium state.

4. Conclusions

The non-stoichiometric equilibrium model was successfully implemented using the RAND algorithm. The energy balance calculations were improved in this study with respect to previous code versions found in Li (2002) and Sakaguchi (2010). The model was used to evaluate the influence of the amount of gasification medium on gasification with air, steam and combinations of those.

The results suggest maximum efficiency of air gasification at equivalence ratios close to 0.3 for the evaluated biomass (residual sawdust). At higher ERs, the inert nitrogen from the air

dientes the gaseous species with high heating values and the oxygen excess promotes total oxidation reactions which also contribute to decrease the gas heating value. At lower ERs, the heating value of the product gas increases but its volume decreases given the increase of unconverted solid carbon, which reduces the efficiency of the process. In experimental gasification, the loss of the product gas heating value is also evidenced as the ER increases, but its efficiency will always be lower than predicted when using the equivalence ratio suggested by the equilibrium model because part of the carbon from biomass is converted into residual chars and tars instead of gaseous fuels such as CO.

In the case of steam gasification, the equilibrium model estimates that high SC ratios imply a considerable increase of the heat that must be supplied to the system and a decrease in the heating value of the product gas due to the increase of water concentration. However, such a decrease does not occur in the evaluated bubble bed gasifier, rather, there is an increase in the gas heating value because higher steam flows promote chars and tars gasification, therefore, it may be advisable a steam to carbon ratio between 1 and 2 (higher than a SC of 0.6 suggested by the model) to improve the product gas heating value, requiring a moderate additional amount of heat supplied to the process.

Regarding the use of air-steam mixtures as gasification agent, the equilibrium model recommends avoiding the presence of steam in the air gasification at equivalence ratios greater than or equal to 0.3, since the additional heat required causes a significant decrease in efficiency. In the case of steam gasification, at SC ratios greater than or equal to 0.6 the air supply causes a decrease in efficiency due to the loss of heating value in the gas (by dilution in N_2 and production of the oxidized species CO_2 and H_2O), even though the heat required by the gasification decreases considerably due to the heat released by oxidation exothermic reactions. The equilibrium model estimated that when using very low ERs (around 0.05) and low SC ratios (approximately 0.5 at 740 °C and 1 bar for the reference dry biomass) high efficiencies of the equilibrium gasification are obtained. However, as experimental measurements in a bubbling bed gasifier showed that since an improvement in the product gas heating value is seen as the amount of steam in its mixture with air increased, it might be convenient to use more steam than that suggested by the equilibrium model in order to obtained higher gas heating values even though this rises the process heat expenditure. Nevertheless, this energy expense is reduced when using higher equivalence ratios in the air-steam mixture than that suggested by the model to improve the process efficiency, provided that the consequent decrease in the gas heating value is not significant.

The capacity of the model for predicting product gas compositions was verified by comparison with experimental data from literature. Eve though, there is a deviation between the results, the model is capable of showing the tendency of the process yield when conditions are modified. The deviations between model and experimentation can be explained based on the assumptions made during the construction of the model. This means that the model can be improved to predict results more accurately.

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