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**MODELING BIOMASS GASIFICATION:
A NEW APPROACH TO UTILIZE RENEWABLE SOURCES OF ENERGY**

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ABSTRACT

Thermochemical equilibrium modeling is the basis of the numerical method implemented in this study to predict the performance of a biomass gasifier. To validate the model, a close agreement is shown between numerical and experimental results. The model is then used in order to optimize the selection procedure of a specific biomass for a certain application. For this purpose, the minimum and maximum amount of carbon, hydrogen, and oxygen for 55 different biomass materials are extracted to calculate the range of variation of oxygen content and carbon/hydrogen ratio. The influences of such variations on syngas characteristics are then studied. Syngas characteristics are comprised of syngas calorific value, outlet gas temperature, gasification efficiency, and the volume of syngas obtained. The results are plotted in a generalized format that may be used for a wide range of biomass materials. These plots can be used for the selection of a biomass material based on desired conditions. Therefore, the developed model in this study provides a tool for design optimization of a biomass downdraft gasifier.

INTRODUCTION

Controversial projections about natural gas reserves depletion by the 1980s and 1990s, the oil embargo of 1973, and more restrictive and stringent environmental standards provided incentive for both governments and industries to explore and promote the commercialization of new sources of fuel, such as biomass, and also new technologies in order to utilize them [1]. The term biomass covers a broad range of materials that have one thing in common; they are all derived

from recently living organisms, such as agricultural and forestry wastes, as well as purpose-grown materials as biomass. The utilization of biomass as a fuel is largely restricted to the use of by-products from forestry, as well as pulp and paper and sugar industries. Nonetheless, its use is being encouraged as part of a strategy for CO_2 abatement [2-3]. Reuse and recycling, composting, incineration, and land filling are four main categories of acceptable biomass handling options from which the last two are the most frequently used methods [4]. More recently, gasification of biomass materials has also been introduced as another kind of waste to energy (WTE) conversion; a thermochemical process to convert carbonaceous materials to a synthesis gas (syngas). One of the attractive features of this technology includes the ability to produce a clean syngas that can be used for either generating electricity or producing chemicals.

For the complete combustion of biomass, the theoretical amount of air required (stoichiometric quantity) is 6 to 6.5 kg air/kg biomass. The final products are CO_2 and H_2O . In gasification, biomass is subjected to partial pyrolysis under sub-stoichiometric conditions with the air quantity being limited to 1.5 to 1.8 kg air/kg biomass. The resultant mixture of gases produced contains mainly CO , H_2 , and CH_4 and is combustible.

The overall process of common gasification can be divided into four steps [1] which may occur sequentially or simultaneously, depending on the reactor design and the feedstock material. These steps are comprised of drying, pyrolysis (devolatilization), gasification, and combustion. The combustion step provides the thermal energy that derives

gasification reactions. Standard gasification technologies do not use any external heat source and rely on the process itself to sustain the reaction [5]. Nevertheless, external heat source is used by some technologies, i.e. plasma gasification, leaving the gasifier with the need of limited combustion, which is environmentally preferable.

The quality of syngas produced can vary as a function of gasifying agent and the process operating conditions. Obtained syngas can cover a range of calorific values including low CV (4-6 MJ/m³), medium CV (12-18 MJ/m³), and high CV (40 MJ/m³). Low CV syngas is obtained when air is used as gasifying agent. Steam or hydrogen leads to produce medium or high CV syngas. It can be seen that while a range of syngas qualities can be produced, economic factors are a primary consideration [6]. However, even low CV syngas can be combusted at a relatively high efficiency and with good degree of control without emitting smoke. The many advantages of gasification over combustion make it feasible to review the possibilities of syngas production as a sink for biomass materials, while observing the environmental regulations.

Biomass gasifiers are complex equipments that require a lot of time to be mounted and to be put in operation; make it difficult to explore various working conditions. As a result, some mathematical models were made to predict the performance of the gasifiers. Recent theoretical studies include kinetic or non-equilibrium modeling of the reduction reactions of a downdraft biomass gasifier. These models describe the char reduction process using kinetic rate expressions obtained from experiments and permit better simulation of the experimental data where the residence time of gas and biomass is relatively short. The kinetic model of Wang et al. [7] is based on a mechanism of surface reactions in the reduction zone assuming a given residence time and reaction temperature.

Thermodynamic equilibrium calculations are also used widely in order to predict the thermodynamic limits of chemical reactions describing the gasification process. Since this approach is independent of the gasifier design, it is frequently used in studying of the influence of important fuel/process parameters [8].

Although, thermochemical equilibrium, in reality, never takes place during gasification [9], many works were performed to demonstrate the applicability of the equilibrium models to this process [10-17]. These models are especially true at the high temperatures that occur on the entrained flow gasifiers, where the reaction temperatures are above 1500K [18]. Recent modeling efforts include the application of chemical equilibrium modeling for biomass gasification [11-14]. Some models are based on the minimization of Gibbs free energy [14-15] while others use the idea of equilibrium constants. Among these models, Ruggiero et al. [14] developed a simple model for biomass gasification considering the Gibbs free energy of reaction and emphasized the potential of an equilibrium model. The models of Zainal et al. [16] described the equilibrium composition using water-gas shift and methane (hydrogenating gasification) reactions. The predictions of Zainal et al. [16] highlighted the effect of moisture content in

wood chips and the reaction temperature on syngas composition for a given bed temperature using different biomass materials. Ruggiero et al. [14] and Zainal et al. [16] confirmed that the residence time of the reactants can be considered to be high enough to reach chemical equilibrium. Vaezi et al. [12-13] took the advantage of such approach in order to simulate the gasification process of 20 different biomass materials in order to find the most energetic one. Altafini et al. [19] and Malgar et al. [20] reported a similar conclusion regarding the influence of air/ fuel ratio in addition to biomass moisture content on adiabatic temperature, gas composition and efficiencies. From the exhaustive literature review, it is observed that most of the equilibrium models of biomass gasification developed in the past: describe the governing equations; investigate the effects of operational conditions on gasification characteristics; study the gasification process of a specific feedstock; try to acquire optimum operational conditions; and analyse the effect of variation of operational conditions on the quality of downstream products such as methanol.

In this paper, in order to optimize the selection procedure of a specific biomass for a certain application, a novel procedure is developed and presented. We used the detailed composition of various biomass materials published by National Renewable Energy Laboratory of United States [21] for a list of 55 different biomass materials of different families together with their proximate and ultimate analysis (see Tab.1). This list was used to extract the minimum and maximum amount of carbon, hydrogen, and oxygen from the ultimate analysis of each biomass material, whereas for nitrogen, sulfur, and ash the average data were considered. The model was used in numerous cases for a wide range of values for oxygen and carbon/hydrogen ratio. Thus, the results obtained from the simulation of the gasification process including syngas characteristics were plotted in a generalized format that may be used for a wide range of biomass materials. Such plots can provide the possibility of selection of a biomass material based on desired conditions such as maximum efficiency, calorific value, volume of syngas obtained, optimum gasification temperature, etc. Therefore, the developed model in this study can be used in the design optimization of a biomass downdraft gasifier.

Fuel	RDF	Wood	Wood	Straws	Wood	Willow	Currency
Type	Tacoma	Yard Waste	Demolition	Rice	Forest Residuals	SA22-1Yr	Shredded
Ultimate Analysis							
Carbon	39.70	41.54	46.3	38.24	50.31	49.75	42.89
Hydrogen	5.78	4.79	5.39	5.20	4.59	6.00	5.97
Oxygen	27.24	32.21	34.5	36.84	39.99	42.01	43.62
Nitrogen	0.8	0.85	0.57	0.87	1.03	0.65	1.75
Sulfur	0.35	0.24	0.12	0.18	0.11	0.09	0.30
Ash	26.13	20.37	13.12	18.67	3.97	1.50	5.47
Moisture	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
HHV(KJ/Kg)	15521	16288	18396	15073	20149	19654	18282

Tab. 1: Samples of 55 biomass materials used within the simulations

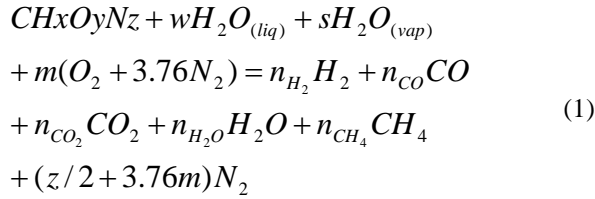
MATHEMATICAL MODEL

A zero dimensional model presented in this paper takes the advantage of thermochemical equilibrium approach which is based on equilibrium constants. The main assumptions of the developed model are as follows:

- The residence time of the reactants is supposed to be high enough to establish chemical equilibrium.
- The gasifier is considered to be adiabatic.
- All gases are presumed to behave ideally.
- All carbon in biomass is assumed to be gasified and, therefore, the formation of char is neglected.
- Ash in biomass is assumed to be inert; i.e. it does not participate in the chemical reactions.
- The syngas is comprised of H_2 , CO , CO_2 , H_2O , CH_4 and N_2 . Tar is not taken into account in the simulation. N_2 is considered to be inert through the gasifier.

The first and main assumption has been demonstrated to be valid by Buekens et al. [10] who stated that for downdraft gasifier designs, both pyrolysis and gasification products are forced through the hottest zone (oxidation zone) so that equilibrium is approximately established after a relatively brief time period. The assumption has also been confirmed in recent works [3,19,22].

The global gasification reaction can be written as follows:

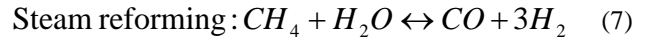
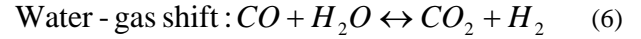
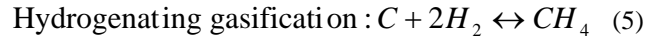
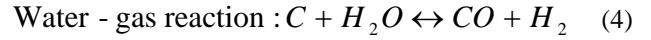
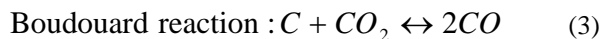


where x, y, and z are numbers of atoms of hydrogen, oxygen, and nitrogen per one atom of carbon in the feedstock; respectively, and w, m, and s are the amounts of water, air, and steam per one kmol of feedstock, respectively. All inputs on the left-hand side of eq. (1) are defined at 25°C. On the right-hand side, n_i is the number of moles of the species i which is also unknown. Molar quantity of water per one kmol of biomass can be written as:

$$w = \frac{M_{bm} \times MC}{M_{H_2O} \times (1 - MC)} \quad (2)$$

where M_{bm} and M_{H_2O} are the masses of the biomass and water; respectively, and MC is the moisture content. Air/fuel ratio can be calculated as $(\alpha + 0.25\beta - 0.5\gamma)$ for a fuel with a chemical formula of $C_\alpha H_\beta O_\gamma N_\zeta$ [23]. During the gasification process, biomass is subjected to partial pyrolysis under sub-stoichiometric conditions. Therefore, m (equivalence ratio) is assumed to be a fraction of the calculated stoichiometric air (30% - 60%).

The following simplified chemical formulas describe the basic gasification process:



The arrows indicate that the reactions are in equilibrium and can proceed in either direction, depending upon the temperature, pressure, and concentration of the reacting species. Higman and van der Burgt [2] showed that eqs. (3) and (4) can be combined to give the water-gas shift reaction (eq. (6)).

For the development of an equilibrium model approach, the number of independent reactions has to be determined by applying the phase rule, as described by Tassios [24]. In the case where no solid carbon remains in the equilibrium state, as in the present model, only two independent reactions need to be considered for the equilibrium equations. Two common approaches are reported in the literature to select/utilize the above mentioned independent equations:

- Selection of water-gas shift reaction together with hydrogenating gasification as the main gasification reactions [16], or
- Selection of water-gas shift reaction along with the steam reforming [8-22].

According to the thermodynamic theory of independent reactions, there is no significant difference between the above reported modeling efforts [24]. The only point that differentiates the equilibrium reactions is that the steam reforming reaction is more favored in the case of steam gasification (high feed water content) [25]. Therefore, water-gas shift reaction together with hydrogenating gasification is chosen to play the role of two independent equations. These equations with their equilibrium constants generate two of five equations required to obtain the five unknown species of the produced syngas (H_2 , CO , CO_2 , H_2O , and CH_4). The remaining three equations are formulated by balancing each chemical element consisting of carbon, hydrogen and oxygen.

The equilibrium constants for the gasification processes can be written based on the following:

$$K = \prod_i (x_i)^{v_i} \left(\frac{P^\circ}{n_{total}} \right)^{\sum v_i} \quad (8)$$

where x_i is mole fraction of the species i in the ideal gas mixture, v is the stoichiometric number, P° is the standard pressure (1atm) and n_{total} is the total number of moles of produced gas. As a result, the equilibrium constants for the water-gas shift reaction and the hydrogenating gasification will be as follows:

$$k_1 = \frac{(n_{CO_2})(n_{H_2})}{(n_{CO})(n_{H_2O})} \quad (9)$$

$$k_2 = \frac{(n_{CH_4})}{P^\circ (n_{H_2})^2} \quad (10)$$

The values of the equilibrium constants, which are only functions of temperature, can be calculated using the Gibbs free energy:

$$\ln k = \frac{-\Delta G_T^\circ}{\tilde{R}T} \quad (11)$$

where \tilde{R} is the universal gas constant and ΔG_T° is the standard Gibbs function of formation. The dependence of ΔG° on temperature can be written as follows:

$$\frac{d(\Delta G^\circ / RT)}{dT} = \frac{-h_f^\circ}{\tilde{R}T^2} \quad (12)$$

where h_f° is the enthalpy/heat of formation. The amounts of h_f° and ΔG° of common combustion products can be found in combustion/chemical engineering books/handbooks [23,26,27]. Heat of formation of biomass is calculated using Souza-Santos' formula [28], which has been presented for solid fuels, as follows:

$$h_{f, fuel}^\circ = \text{LHV}_{dry, fuel} + \frac{1}{M_{fuel}} \sum_{j=prod} n_j h_{f, j}^\circ \quad (13)$$

where LHV is the lower heating value of the fuel and n_j represents stoichiometric coefficients of products of complete combustion of the same fuel. LHV of the fuel is obtained via its higher heating value (HHV). In order to calculate HHV of the biomass materials, three empirical relations based on the composition of main elements (in wt%) C, H, and O are examined, as follows:

Chang's formula[Ref.1]:

$$\text{HHV(MJ/Kg)} = -1.3675 + 0.3137C + 0.7009H + 0.0318O \quad (14)$$

Demirbas'formula[Ref.1]:

$$\text{HHV(MJ/Kg)} = (33.5C + 142.3H - 15.4O - 14.5N) \times 10^{-2} \quad (15)$$

Friedl's formula[Ref.3]:

$$\text{HHV(MJ/Kg)} = 3.55C^2 - 232C - 2230H + 51.2C \times H + 131N + 20600 \quad (16)$$

The discrepancies between experimental data and numerical results obtained via the above relations are plotted in

fig. 1. As observed, eq. (16) is the most accurate one with errors mainly in the range of $\pm 2.6\%$; as a result, it is considered in this study for the calculation of HHV of the biomass materials.

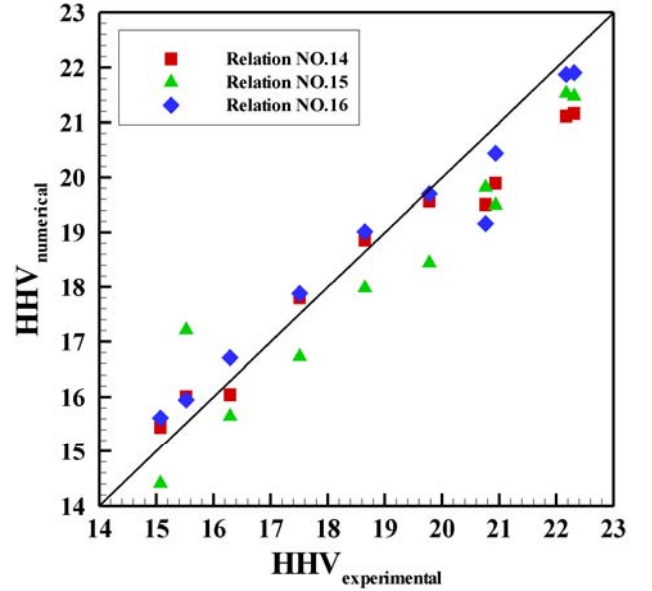


Fig. 1: Discrepancies between experimental data and numerical results obtained using eqs. 14, 15 and 16 for calculation of HHV of biomass materials

Considering eq. (12) along with eq. (11) leads to:

$$\frac{d \ln k}{dT} = \frac{h_f^\circ}{\tilde{R}T^2} \quad (17)$$

Since the heat of formation is a function of T, eq. (17) can be integrated as follows:

$$\ln k = \int \frac{h_f^\circ}{\tilde{R}T^2} dt + I \quad (18)$$

h_f° is linked to temperature, based on the following equation:

$$\frac{h_f^\circ}{\tilde{R}} = \frac{J}{\tilde{R}} + (\Delta A)T + \frac{(\Delta B)}{2}T^2 + \frac{(\Delta C)}{3}T^3 - \frac{(\Delta D)}{T} \quad (19)$$

where I (the constant of integration in eq. (18)) and J are constants and ΔA , ΔB , ΔC , and ΔD are the coefficients for determining the specific heat [27]. Having known the I and J constants together with h_f° and ΔG° , the equilibrium constant (k) can be determined. For instance, the equilibrium constant for water-gas shift reaction is obtained as follows:

$$\ln k_1 = \frac{5878}{T} + 1.86 \ln T - 0.27 \times 10^{-3} T - \frac{58200}{T^2} - 18 \quad (20)$$

Jarungthammachote et al. [29] multiplied equilibrium constants by a factor to improve the performance. The same factor is multiplied by k in the present model.

The temperature of the gasification zone also needs to be determined in order to calculate the equilibrium constants. For this reason, a balance of either energy or enthalpy is performed on the gasification process. If the temperature in the gasification zone is T and that of the inlet state is assumed to be 298 K, the enthalpy balance for this process can be written as:

$$\sum_{j=react} n_j (h_{f,j}^\circ + \Delta h_{T,j}^\circ) = \sum_{i=prod} n_i (h_{f,i}^\circ + \Delta h_{T,i}^\circ) \quad (21)$$

where Δh_T° represents the enthalpy difference between any given state and the reference state. It can be approximated by:

$$\Delta h_T^\circ = \int_{298}^T \bar{C}_p(T) dT \quad (22)$$

where $\bar{C}_p(T)$ is the specific heat at constant pressure which is only a function of temperature. It is considered to be 1.3 for biomass materials [23]. It is also defined by an empirical relation for gasification products [27] as follows:

$$\bar{C}_p(T) = C_1 + C_2 \left[\frac{C_3/T}{\sinh(C_3/T)} \right]^2 + C_4 \left[\frac{C_5/T}{\sinh(C_5/T)} \right]^2 \quad (23)$$

When the equilibrium constants are defined, a system of equations will be obtained that need to be solved. Because of the non-linear nature of some of the equations, the Newton–Raphson method together with specific convergence strategies is used; the equations are solved with an iterative procedure. The procedure starts with an initial guess for the gasification temperature. Equilibrium constants are then calculated and the set of equations are subsequently solved to obtain the syngas composition which in turn is used to determine the new gasification temperature. This iterative procedure continues until the gasification temperature does not change within a certain limit (much less than 1 K) in successive iterations.

MODEL VALIDATION

In order to validate the model, certain cases are selected for which measurements are available in the literature. Jayah et al. [30] took the advantage of a 80 KW test gasifier in order to gasify rubber wood; Wander [31] utilized a fixed bed type, downdraft gasifier to process sawdust; Alauddin [32] studied performance and characteristics of a biomass (wood) gasifier

system; and finally Dogru et al. [33-34] examined the effects of operational conditions on the process of gasification of leather residue in a downdraft gasifier. Ultimate analyses of feedstock used in these experiments are shown in Tab.2.

Fuel	Rubber Wood	Sawdust Wood	Leather Residue
Ultimate Analysis			
Carbon	50.6	52.0	43.59
Hydrogen	6.5	6.07	6.95
Oxygen	42.0	41.55	32.28
Nitrogen	0.2	0.28	10.84
Sulfur	0.0	0.0	1.45
Ash	0.7	0.1	0.0
Total	100.0	100.0	100.0
Moisture Content	18.5	11.0	11.23
HHV (MJ/Kmol)	461.56	470.45	513.87

Tab. 2: Ultimate analyses of feedstock used in certain experiments

The developed numerical model is set up four times in accordance with the above individual experiments, based on feedstock properties and experimental operating conditions. The obtained syngas compositions are then compared to those of the experiments and the results are shown in Table 3. Figure 2 also gives a more perceptible illustration from comparison between numerical results and experimental data. The preferred criteria in order to quantify the amount by which numerical results differ from experimental values is the root mean square error (RMSE), which is the square root of the variance. This error is known as the standard error that summarizes the overall error [35].

	Reference [30] ^a		Reference [31] ^b		Reference [32] ^c		Reference [33-34] ^d	
	Exp	Model	Exp	Model	Exp	Model	Exp	Model
H ₂	17.2	16.5	14.0	15.4	15.23	17.8	10.5	13.76
CO	19.6	20.0	20.14	22.2	23.04	20.7	16.89	17.7
CH ₄	1.4	1.12	2.31	1.2	1.58	2.0	1.49	0.35
CO ₂	9.9	10.7	12.06	9.7	16.42	12.1	70.6	65.31
N ₂	51.9	51.4	50.79	51.1	42.31	47.2		
HHV(MJ/m ³)-	5.08	5.2	5.2	4.85	5.69	4.92	4.13	
RMS error	0.56	1.62	3.32	3.74				

Tab. 3: Comparison between numerical results and measurements [30 - 34] for syngas produced from four biomass materials.

- rubber wood – 18.5% moisture content
- sawdust – 11% moisture content
- wood – 20% moisture content
- leather residue – 11.23% moisture content

$$e) \text{ RMS} = \sqrt{\frac{\sum_{i=1}^N (\text{Experimental}_i - \text{Numerical}_i)^2}{\text{Number of species}}}$$

It is observed that for CH_4 , the developed equilibrium model slightly under predicts the experiments as shown in Tab.3. This is expected for all equilibrium models because the equilibrium constant of the hydrogasification reaction tends to zero at the elevated temperatures prevailing in the reduction zone [36]. As a result, the predicted CH_4 concentration in the final gas is small. In a real gasifier, however, devolatilization of fuel gives high contents in CH_4 and higher hydrocarbons (e.g., C_xH_y), which do not react completely to equilibrium concentrations of CO , CO_2 , and H_2 . Therefore, an equilibrium state is not established and higher methane content is detected in the measurements [22].

As observed from Tab.3 and fig. 2, the results of the developed model agree well with those of the experiments for the syngas composition and its calorific value. This comparison validates the model and its underlying assumptions.

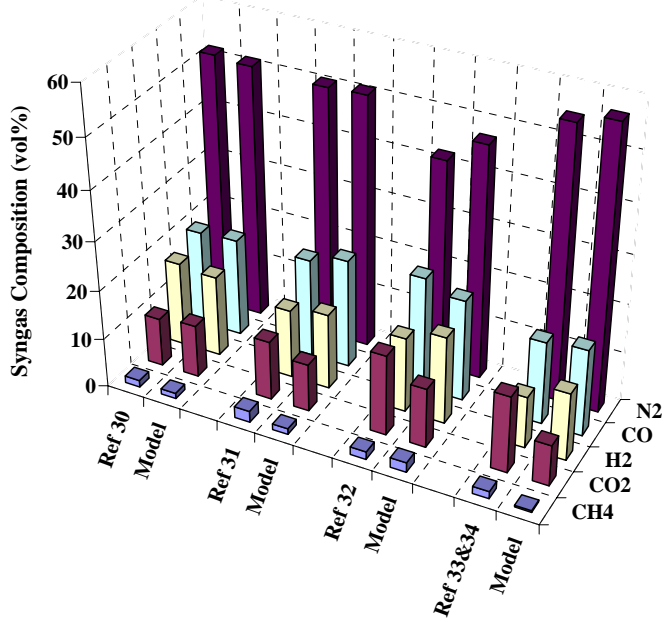


Fig. 2: Graphical comparison between numerical and experimental results

RESULTS AND DISCUSSION

In this section, the influence of different fuel compositions on syngas characteristics is examined first. Syngas characteristics which are studied are comprised of gasification efficiency, outlet gas temperature, the volumetric rate of the obtained syngas and its calorific value. The examination process is done by means of varying oxygen content on one hand and the ratio of carbon to hydrogen content on the other (C/H ratio). This variation is carried out over a wide range of fuel compositions: oxygen contents from 27 to 44 wt%, carbon content from 38 to 53 wt%, and hydrogen content from 4.6 to 6.7 wt%, which results in C/H ratio to vary from 5.75 to 11.65. The above data are extracted from the detailed composition of various biomass materials published by National Renewable Energy Laboratory of United States [21] for a list of 55 different biomass materials of different families (Tab.1).

Regarding other elements including nitrogen, sulfur, and ash, instead of the range of the variations, the average data are used in the model. In order to get comparable results, dry-based analyses (moisture content equal to zero) are considered. Moreover, all operational conditions are kept constant, as follow:

- Equivalence ratio: 0.4
- Gasification pressure: 1 atm
- Gasifying agent: air
- Air inlet temperature: 298 K
- Fuel inlet temperature: 298 K
- Steam injection: no

The results for the gasification characteristics are plotted in a generalized format that may be used for a wide range of biomass materials, as shown in figs. 3 to 7. Samples of biomass materials are also placed, which are outspread through the range of oxygen content with properties presented in Tab.1.

Fig. 3 explains how higher heating value (HHV) of the produced syngas varies with respect to oxygen content and C/H ratio. As observed, the influence of C/H ratio on HHV is much higher than that of the oxygen content. An increase in C/H ratio to about 8.2 leads to the increase in HHV of the produced syngas. Any further increase in C/H ratio results in the reduction of HHV. The possibility to select a biomass which produces syngas with an HHV equal to 370 MJ/Kmol seems to be interesting. This calorific value is about 80% of the calorific value of the most of biomass materials. The losses being accounted for by the syngas sensible heat, the ash heat content, and the radiation losses.

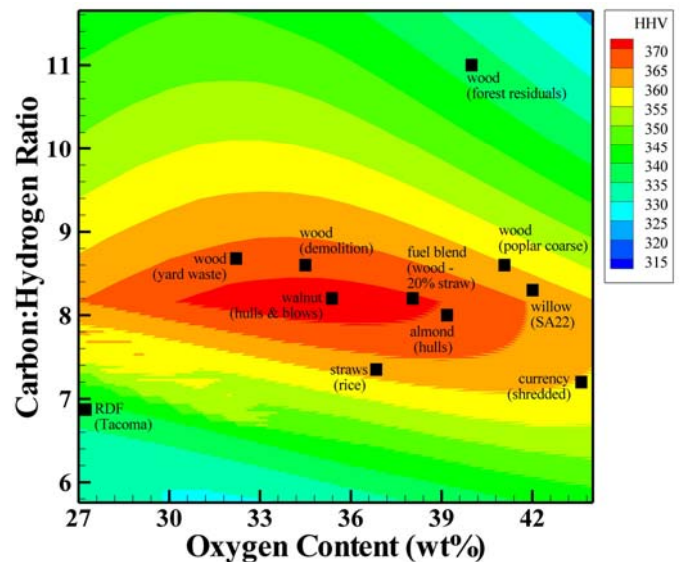


Fig. 3: Higher heating value of the produced syngas (MJ/Kmol) based on the oxygen content and C/H ratio of the biomass materials.

Figures 4 and 5 display the CGE (cold gas efficiency) and CCE (carbon conversion efficiency), respectively. These efficiencies are defined as follows:

$$CGE = \frac{\text{Heating value in produced syngas [MJ]}}{\text{Heating value in feed stock [MJ]}} \times 100 \quad (24)$$

$$CCE = \left\{ 1 - \frac{\text{Carbon in gasification residue [kmol]}}{\text{Carbon in feedstock [kmol]}} \right\} \times 100 \quad (25)$$

Figure 4 shows that the highest cold gas efficiency is obtained at the lowest C/H ratio and oxygen content. As the oxygen content of the feedstock increases, the influence of C/H ratio on the CGE increases. Over the main part of the plotted domain in fig. 4, the CGE does not drop below 75% and its average value is about 80%.

The oxygen content and C/H ratio have a small effect on the CCE as shown in Fig. 5. The CCE experience variations at low oxygen contents and C/H ratio, but the rate of the variations reduces as both oxygen content and C/H ratio increases. Over the entire domain of the plot, the CCE exceeds 84% which is considerable. It can be concluded, therefore, that for a wide range of oxygen content and C/H ratio, it is possible to reach a CCE more than 86%.

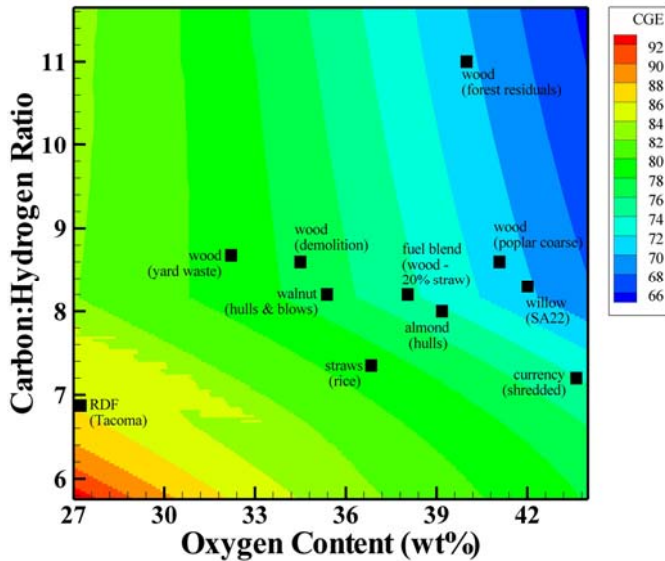


Fig. 4: Cold gas efficiency of the produced syngas (%) based on the oxygen content and C/H ratio of the biomass materials.

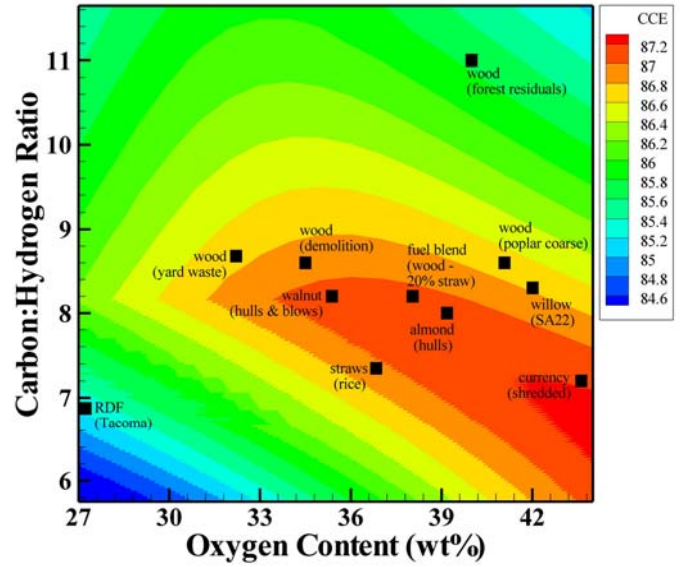


Fig. 5: Carbon conversion efficiency of the produced syngas (%) based on the oxygen content and C/H ratio of the biomass materials.

Fig. 6 shows the produced syngas temperature distribution. An increase of the oxygen content and C/H ratio increases the temperature.

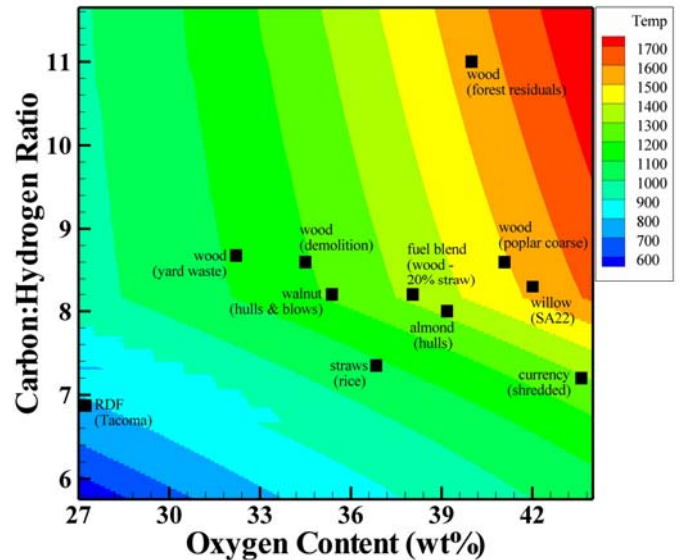


Fig. 6: Variation of the produced syngas temperature (in K) based on the oxygen content and C/H ratio of the biomass materials.

Considering the produced syngas to behave ideally, makes it possible to calculate the volume of the syngas produced per one unit mass of the biomass, as follows:

$$PV = n\tilde{R}T \quad (26)$$

where P , V , n , \tilde{R} , and T represent pressure (KPa), volume (m^3), number of moles of gaseous species, universal gas constant (KJ/Kmol.K), and Temperature (K), respectively. Fig. 7 displays the syngas volume with respect to the oxygen content and C/H ratio. As expected, based on eq. (26), the more the syngas temperature is, the more the syngas volume is obtained. Therefore, the pattern of variations of syngas temperature and syngas volume is similar (comparing figs. 6 and 7). It is interesting to note that per one kilogram of biomass a syngas volume of up to 9 m^3 (in atmospheric pressure) can be obtained.

CONCLUSION

A thermochemical equilibrium model was developed to simulate the gasification process of biomass materials and predict the composition of the produced syngas. The predicted results agreed well with those of the experiments available in the literature. The model was then employed in order to optimize the selection procedure of a specific biomass for a certain application. For this purpose, the detailed composition of various biomass materials published by National Renewable Energy Laboratory of United States [21] was used to extract the minimum and maximum amount of carbon, hydrogen, and oxygen.

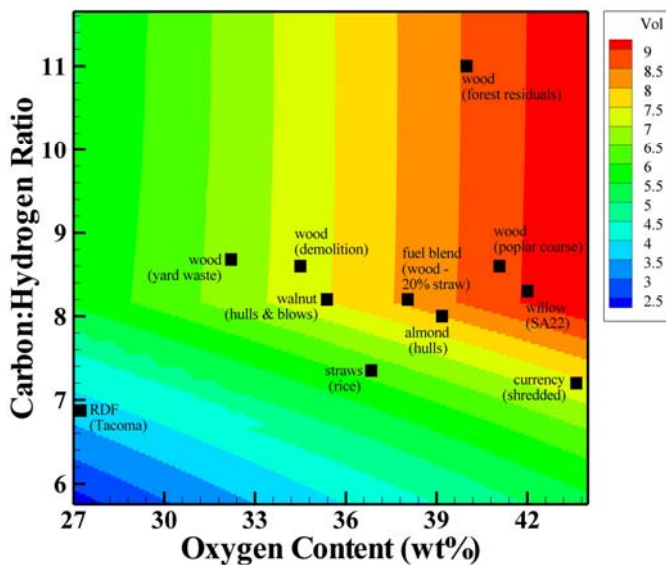


Fig. 7: Volume of syngas produced (m^3) per 1 Kg biomass based on the oxygen content and C/H ratio of the biomass materials.

Next, the influences of varying C/H ratio together with oxygen content on syngas characteristics were investigated. They included the calorific value, gasification efficiencies, outlet gas temperature, and the volume of produced syngas. Dry-based analyses and constant operational conditions were considered in order to obtain these results.

The results of simulation for the gasification process and the syngas characteristics were plotted in a generalized format that may be used for a wide range of biomass materials.

Increase in C/H ratio up to about 8.2 led to an increase in HHV of the produced syngas. Over the main part of the considered domain for oxygen content and C/H ratio, the CGE did not drop below 75% and its average value was about 80%. The CCE for the same domain exceeded 84%. It was shown that for a wide range of oxygen content and C/H ratio, it was possible to reach a CCE more than 86%. At the maximum values considered for the oxygen content and C/H ratio, the produced syngas could reach a temperature as high as 1700 K.

The various plots presented in this paper can provide the possibility of the selection of a proper biomass material based on the desired conditions for the maximum efficiency, calorific value, volume of the syngas, optimum gasification temperature, etc. Therefore, the developed model in this study can be used in the design optimization of a biomass downdraft gasifier.

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