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On a methodology for selecting biomass materials for gasification purposes

M. Vaezi [a,*], M. Passandideh-Fard [b], M. Moghiman [b], M. Charmchi [c]

[a] Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada
[b] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[c] Department of Mechanical Engineering, University of Massachusetts, Lowell, MA, USA

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ABSTRACT

The purpose of this study is to provide a methodology for the selection of appropriate biomass feedstocks for gasification purposes based on the final syngas applications. To achieve this objective, a numerical algorithm is developed to simulate the gasification process of biomass materials. The model is first validated by a close agreement found between the numerical results and those of the experiments available in the literature for fixed-bed downdraft gasifiers. Subsequently, a list of 80 diverse biomass materials of distinctive families, together with their proximate and ultimate analysis is utilized to extract the extreme limits of carbon, hydrogen, and oxygen contents. The gasification process is then simulated in numerous cases covering a comprehensive range of biomass oxygen content and carbon:hydrogen ratio, while operational conditions are kept constant. The obtained results, comprising syngas key characteristics are plotted at last in a generalized format. The approach novelty rests on providing a set of figures that can be used to select a type of biomass to achieve certain syngas specifications in a moving/fixed bed gasifier at the atmospheric pressure.

1. Introduction

With the depletion of fossil fuels, as well as their increasing price and undesirable environmental effects, the utilization of biomass is getting increased attention as a potential resource of renewable energy. Thanks to its renewability, abundant availability, and carbon dioxide neutrality, biomass is considered to be one of the most promising resources for the production of future fuels [1–3]. Present biomass share in the world total primary energy consumption is about 12% and it is estimated to be increased to near 15% by 2010 in developed countries [4,5].

Amongst the diverse methods of converting biomass materials to bio-fuels, gasification is the most mature thermo-chemical conversion technology available. Gasification process offers technologically more attractive options, economically the lowest dependency on the feedstock cost [6,7], and environmentally a more friendly way of exploiting biomass materials. The presence of non-oxidation conditions, which makes the gasification distinguished from the combustion process, causes the pollutant emissions to be considerably reduced [8].

The thermo-chemical conversion of biomass materials has been extensively studied both experimentally and theoretically by a large number of researchers. Majority of the investigators focused on the design and operation of the gasifiers [9–11], as well as gasifying process [12–14] and composition of the synthesis gas (syngas) produced [15–17]. The common criteria, usually considered in the procedure of choosing a suitable feedstock, are limited to its abundance and availability. Although the majority of published literatures used such an approach, it cannot necessarily satisfy the requirements of all case studies. For example when a wide range of feedstock is available, the selection of a specific biomass for a gasification process may be desired with a requirement that the resulting syngas has certain characteristics, such as specific calorific value, etc.

Regarding the selection of an appropriate biomass for gasification-related purposes, it has seldom been considered as a pre-gasification procedure. The objective of the present paper is to introduce a methodology to select biomass materials based on the gasification conditions and syngas final applications. Utilizing such an approach, it becomes possible to accurately choose a feedstock while being sure that its gasification under given operating conditions results in a syngas with the desired gasification characteristics.

In this paper, first a numerical model is developed for simulating the gasification process of biomass materials; the model takes the advantage of thermo-chemical equilibrium approach based on equilibrium constants. The combination of the laws of conservation of energy in an open system, conservation of atomic species, and the laws of chemical equilibrium provides a numerical algorithm that can be used in predicting the composition of syngas, and investigating the effect of important variables on gasification characteristics. To validate the model, the results of simulations are compared with those of the experiments [18–22]. In the next step, a list of 80 different biomass materials of distinctive families together with their proximate and ultimate analysis [23,24] is used to extract the extreme limits of carbon, hydrogen, and oxygen contents of biomass materials based

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* Corresponding author at: Postal address: 4-9 Mechanical Engineering Building, Edmonton, AB, Canada T6G 2G8. Tel.: +1 780 938 4479; fax: +1 780 492 2200.
E-mail address: mvaezi@ualberta.ca (M. Vaezi).

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on their ultimate analysis; however for nitrogen, sulfur, and ash, the average data is considered. The gasification process is then simulated in numerous cases of biomass materials with a wide range of oxygen content and carbon:hydrogen (C:H) ratio, while operating conditions are kept constant. The obtained results, comprising syngas characteristics, are plotted in a generalized format that can be employed for a wide range of biomass materials. These plots provide the possibility of selecting the appropriate biomass for gasification purposes based on the desired syngas characteristics such as maximum efficiency, calorific value, optimum gasification temperature, etc.

2. Numerical method

The numerical algorithm presented takes the advantage of thermo-chemical equilibrium approach, based on equilibrium constants. The same approach was utilized in a previous paper by the authors [25], where its accuracy and reliability were well validated. The main assumptions of the model are as follows: the residence time of the reactants is supposed to be high enough to establish chemical equilibrium; all carbon in biomass is assumed to be gasified and, therefore, the formation of char is neglected; the syngas is composed of H_2, CO, CO_2, H_2O, CH_4 and N_2; tar is not taken into account in the simulation; and the gasifier is considered to be adiabatic. The first assumption has been demonstrated to be valid by Buekens et al. [26] and has been confirmed in more recent works [27–29].

To develop the numerical model, the chemical formula of the feedstock is defined as CH*x*O*y*N*z*. The global gasification reaction can be written as:

$$\begin{gathered}\mathrm{CH}x\mathrm{O}y\mathrm{N}z + wH_2O_{(liq)} + sH_2O_{(vap)} + m(O_2 + 3.76N_2) = n_{H_2}H_2 + n_{CO}CO \\ + n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{CH_4}CH_4 + (z/2 + 3.76m)N_2.\end{gathered} \tag{1}$$

Concentrations of H_2S and NH_3 are negligible [30] and, therefore, are not considered in the simulation. During the gasification process, the feedstock 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%) [31].

For the development of an equilibrium model, the number of independent reactions has to be determined by applying the phase rule, as described by Tassios [32]. 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. Two common approaches are reported in the literature to select/utilize the above-mentioned independent equations: the selection of water–gas shift reaction together with hydrogenating gasification as the main gasification reactions [33] or the selection of water–gas shift reaction along with that of the steam reforming [29,34]. According to the thermodynamic theory of the independent reactions, there is no significant difference between the above reported modeling efforts [32]. However, the only point differentiating the equilibrium reactions is that the steam reforming reaction is more favored in the case of steam gasification (high feed water content) [35]. Since no steam injection is considered in the present study, the water–gas shift reaction together with hydrogenating gasification is chosen to play the role of independent equations. The two equations are:

$$\text{Water–gas shift reaction}: CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2}$$

$$\text{Hydrogenating gasification (Methane reaction)}: C + 2H_2 \leftrightarrow CH_4. \tag{3}$$

The equilibrium constants of the above reactions generate two of the five equations required to obtain 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:

$$K = \prod_i (x_i)^{vi} \left(\frac{P^\circ}{n_{total}}\right)^{\sum_i{}^{vi}}. \tag{4}$$

The values of the equilibrium constants can be calculated using the standard Gibbs function of formation (ΔG°), whose dependency on temperature can be described as follows:

$$\frac{d(\Delta G^\circ/RT)}{dT} = \frac{-h_f^\circ}{\tilde{R}T^2}. \tag{5}$$

The heat of formation of biomass (h_f°) is calculated using Souza-Santos' formula [36], which has been presented for solid fuels:

$$h^\circ_{f,fuel} = \mathrm{LHV}_{,dry,fuel} + \frac{1}{M_{fuel}} \sum_{j=prod} n_j h^\circ_{f,j}. \tag{6}$$

In order to calculate the HHV of the biomass materials, which is the basis for obtaining the HHV, three empirical relations based on the composition of the main elements C, H, and O (in wt%) are examined, as follows:

Sheng's formula [37]:

$$\mathrm{HHV(MJ/kg)} = -1.3675 + 0.3137\mathrm{C} + 0.7009\mathrm{H} + 0.0318\,\mathrm{O} \tag{7}$$

Demirbas' formula [38]:

$$\mathrm{HHV(MJ/kg)} = (33.5\mathrm{C} + 142.3\mathrm{H} - 15.4\mathrm{O} - 14.5\mathrm{N}) \times 10^{-2} \tag{8}$$

Friedl's formula [39]:

$$\mathrm{HHV(MJ/kg)} = 3.55\mathrm{C}^2 - 232\mathrm{C} - 2230\mathrm{H} + 51.2\mathrm{C} \times \mathrm{H} + 131\mathrm{N} + 20600. \tag{9}$$

The database BIOBIB [40] contains analytical and calorific data for a wide variety of biomass materials. A selection of the ultimate analysis of the elements along with the measured HHV of the corresponding samples for a variety of biomass origins, has been used for this study. The discrepancies between experimental measurements and calculated values using the above relations are plotted in Fig. 1. As

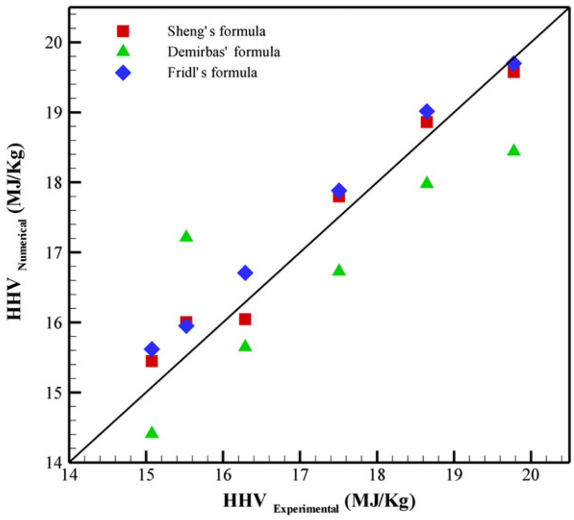

Fig. 1. Discrepancies between experimental measurements [40] and values obtained using Eqs. (7), (8), and (9) for calculating HHV of the biomass materials.

Table 1
Quantitative comparison between numerical results and measurements [18–22] for syngas produced from four various biomass materials.

	Ref.[18][a]	Present model	Ref.[19][b]	Present model	Ref.[20][c]	Present model	Ref.[21,22][d]	Present 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[e] error	0.56		1.62		3.32		3.74	

[a] Rubber wood — 18.5% moisture content.
[b] Sawdust — 11% moisture content.
[c] Wood — 20% moisture content.
[d] Leather residue — 11.23% moisture content.
[e] $\text{RMS} = \sqrt{\frac{\sum_{i=1}^{N}(\text{Experimental}_i - \text{Numerical}_i)^2}{\text{Number of species}}}$.

observed, Friedl's formula presents the most accurate approach with errors mainly in the range of ±2.6%. As a result, it is chosen for calculating the HHV of the biomass materials throughout this paper.

Having known the h_f° and ΔG°, it is possible to determine the equilibrium constant K. As an example, the equilibrium constant for water–gas shift reaction is obtained as follows:

$$\ln K_1 = \frac{5878}{T} + 1.86 \ln T - 0.27 \times 10^{-3} T - \frac{58200}{T^2} - 18. \tag{10}$$

To improve the model accuracy, the equilibrium constants are multiplied by certain factors obtained from a comparison between calculated results and those of the experiments [18–22]. Jarungthammachote et al. [41] used the same approach in their 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 approximated based upon the temperature-dependence specific heat at constant pressure ($\bar{C}_p(T)$). No temperature difference is considered for reactants; feedstock and gasifying agent. However, the specific heat is defined by an empirical relation for gasification products [42] as follows:

$$\bar{C}_p(T) = C_1 + C_2\left[\frac{C_3/T}{\sinh(C_3/T)}\right]^2 + C_4\left[\frac{C_5/T}{\sinh(C_5/T)}\right]^2. \tag{11}$$

When the equilibrium constants are defined, a system of equations will be obtained that need to be solved. Because of the nonlinear nature of some of the equations, the implicit Newton–Raphson method is used where the solution is obtained by an iterative procedure. This enhanced strategy ensured the solution convergence. 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.

3. Model validation

To validate the model, certain cases are selected for which measurements are available in the literature. Jayah et al. [18] took the advantage of a 80 kW downdraft gasifier to gasify rubber wood; Wander [19] utilized a fixed bed type downdraft gasifier to process sawdust; Alauddin [20] studied performance and characteristics of a wood gasifier system; and finally Dogru et al. [21,22] examined the effects of operational conditions on the gasification process of leather residue in a downdraft gasifier. The developed numerical model is set up four times in accordance with the above individual experiments, based on feedstock properties and corresponding experimental operating conditions. The predicted syngas compositions are then compared to those of the experiments and the results are shown in Table 1. The preferred criterion to quantify the difference between numerical results and experimental values, is the root mean square error ($\text{RMSerror} = \sqrt{\sum_{i=1}^{N}(Experiment_i - Model_i)^2/N}$), i.e. the square root of the variance. This error is known as the standard error that summarizes the overall error [43].

As observed in Table 1, 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. It can be seen that for CH_4, the developed equilibrium model slightly underpredicts the experiments. This is expected for all equilibrium models, because the equilibrium constant of the hydro-gasification reaction tends to zero at the elevated temperatures prevailing in the reduction zone [40]. 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 the 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 [29].

4. Results and discussion

Having validated the model, it is used to simulate the gasification process of a wide variety of biomass materials. More than 80 various biomass feedstock from major biomass families[1] [23,24] were analyzed, of which the ultimate and proximate analyses for 11 sample feedstock are presented in Table 2. For the major elements of carbon, hydrogen, and oxygen, the extreme quantity of contents were extracted: oxygen content from 27 to 44 wt.%, carbon content from 38 to 53 wt.%, and hydrogen content from 4.6 to 6.7 wt.%. However, for the nitrogen, sulfur, and ash, the average data were considered: 0.73 wt.%, 0.11 wt.%, and 5.6 wt.%, respectively. The developed numerical algorithm is used to simulate the gasification process with respect to varying feedstock properties. The entire ranges of carbon, hydrogen, and oxygen contents that may exist in a living organic material are swept through a triple loop. Such a sweep practically encompasses all sorts of biomass materials considered in this study.

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[1] Wood and woody biomass (WWB), herbaceous and agricultural biomass (HAB), animal biomass (AB), mixture of biomass, and contaminated biomass (CB).

Table 2
Samples of biomass materials used for the simulations.

Fuel	RDF	Wood	Wood	Walnut	Straws	Fuel blend grate-1	Almond	Wood	Wood	Willow	Currency
Type	Tacoma	Yard waste	Demolition	Hulls and straws	Rice	Wood–20%straw	Hulls	Forest residuals	Poplar-coarse	SA22-1Yr	Shredded
Proximate analysis (db)[a]											
Fixed carbon	0.47	13.59	12.32	17.47	15.86	16.67	20.07	13.62	12.26	16.67	11.67
Volatile matter	73.40	66.04	74.56	79.58	65.47	75.14	73.80	82.41	86.14	81.83	82.86
Ash	26.13	20.37	13.12	2.95	18.67	8.19	6.13	3.97	1.60	1.50	5.47
Moisture	0.0	0.0	0.0	0.0	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	100.0	100.0	100.0	100.0
Ultimate analysis (db)[a]											
Carbon	39.70	41.54	46.3	53.51	38.24	47.48	47.53	50.31	50.82	49.75	42.89
Hydrogen	5.78	4.79	5.39	6.52	5.20	5.81	5.97	4.59	5.89	6.00	5.97
Oxygen	27.24	32.21	34.5	35.38	36.84	38.05	39.18	39.99	41.08	42.01	43.62
Nitrogen	0.8	0.85	0.57	1.53	0.87	0.35	1.13	1.03	0.59	0.65	1.75
Sulfur	0.35	0.24	0.12	0.11	0.18	0.12	0.06	0.11	0.02	0.09	0.30
Ash	26.13	20.37	13.12	2.95	18.67	8.19	6.13	3.97	1.6	1.50	5.47
Moisture	0.0	0.0	0.0	0.0	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	100.0	100.0	100.0	100.0
HHV(KJ/kg)	15,521	16,288	18,396	22,173	15,073	18,784	18,868	20,149	18,915	19,654	18,282

[a] Dry basis.

For each unit increase in the quantity of any major element, the gasification process for corresponding feedstock is simulated and the results are finally plotted in a generalized format. To get comparable results, dry-based ultimate analyses (moisture content equal to zero) are considered. Moreover, all operating conditions are chosen as ordinary as possible and are kept constant during the simulation procedure. These conditions are: equivalence ratio: 0.4; gasification pressure: 1 atm; gasifying agent: air; fuel inlet temperature: 298 K; air inlet temperature: 298 K; steam injection: zero. The value of 0.4 is chosen as the dominant equivalence ratio, because this value has been reported as the optimum ratio to achieve the highest carbon conversion efficiency [44] and syngas calorific value [45], as well as the least outlet gas temperature [46] for a variety of feedstocks, gasifiers, and operating conditions.

In this section, first the syngas characteristics for a wide range of biomass materials are presented. Next, using these extensive results, a practical approach for the selection procedure of appropriate biomass materials for various gasification purposes is introduced.

4.1. Syngas characteristics for various biomass

Figs. 2 to 5 illustrate the final contours for the syngas characteristics plotted with respect to both carbon:hydrogen (C:H) ratio and oxygen content of the feedstock. The incontinuities observed in contours are due to grid size limitation which, at the time of conducting the research, it was not practically possible to make it finer, because of the computing processor technical restrictions and time issues. Samples of biomass materials are also placed on the figures with properties presented in Table 2.

Here it is worth pointing out that analyzing the chemical processes, leading to results shown below, are not the objectives of the present paper. Rather, the focus of the paper is on presenting the methodology and the idea behind, simply by describing the results, and stating how to take the advantage of these results in order to optimize the procedure of choosing appropriate biomass materials for gasification purposes.

Fig. 2 displays how the calorific value (higher heating value or HHV) of the produced syngas varies with respect to the oxygen content and C:H ratio. The syngas calorific value is calculated based on individual calorific values of the energetic gases; H_2, CO, and CH_4. As observed, the influence of the C:H ratio on the calorific value is much higher than that of the oxygen content. The possibility to select a biomass, that if gasified under certain conditions can produce a syngas with a calorific value equal to 370 MJ/kmol seems to be interesting. This calorific value is about 80% of the calorific values of the majority of biomass materials the 20% loss being accounted for by

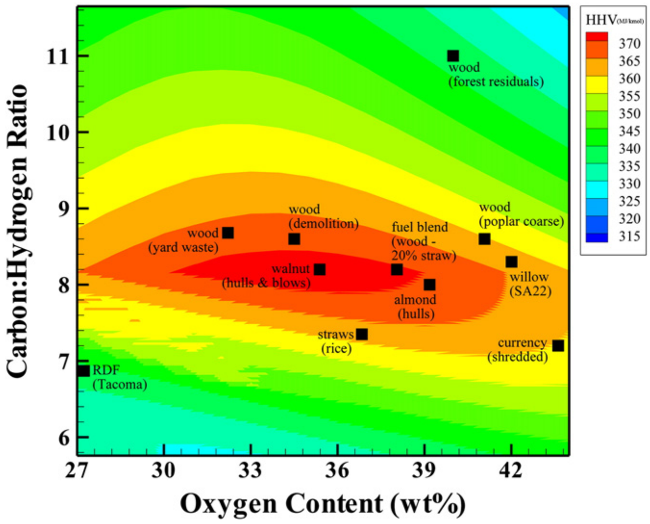

Fig. 2. Calorific value of the produced syngas (MJ/kmol) based on the oxygen content and C:H ratio of the biomass materials.

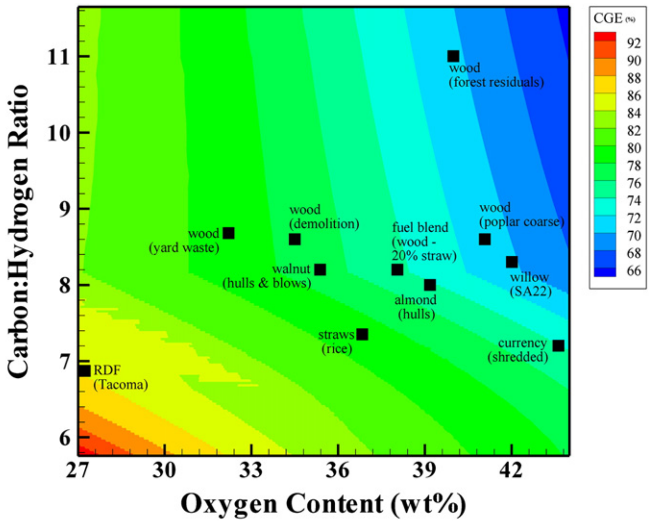

Fig. 3. Cold gas efficiency of the produced syngas (%) based on the oxygen content and C:H ratio of the biomass materials.

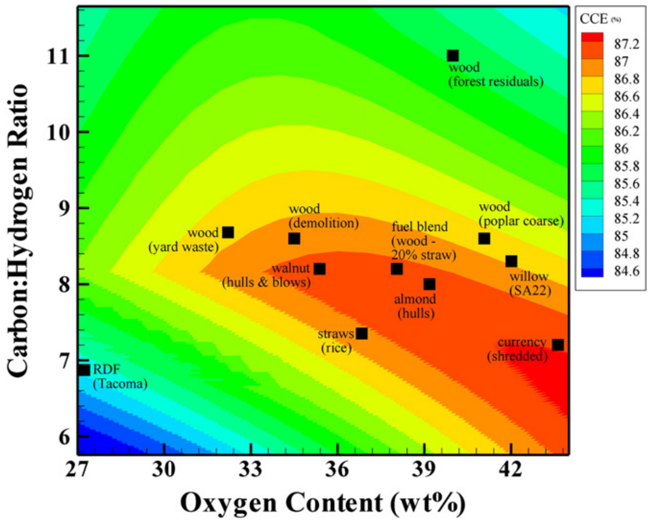

Fig. 4. Carbon conversion efficiency of the produced syngas (%) based on the oxygen content and C:H ratio of the biomass materials.

the syngas sensible heat, and the ash heat content. It should be mentioned that such a noticeable syngas calorific value is achieved under common operating conditions. Increasing either the gasification pressure or the oxygen enrichment, it is possible to reach even a higher calorific value [14,17].

Figs. 3 and 4 display the variations of the cold gas efficiency $\left(CGE = \frac{\text{heating value in produced syngas}[\text{MJ/kmol}]}{\text{heating value in feedstock}[\text{MJ/kmol}]} \times 100\right)$ and carbon conversion efficiency $\left(CCE = \left\{1 - \frac{\text{carbon in gasification residue}[\text{kmol}]}{\text{carbon in feedstock}[\text{kmol}]}\right\} \times 100\right)$ respectively based on the C:H ratio and oxygen content of the feedstock. Regarding the CGE, the energy of the produced syngas and that of the feedstock is evaluated in the same state (reference temperature). Also considering the amount of carbon in the feedstock and produced syngas, the CCE can be calculated.

Fig. 3 shows that the highest cold gas efficiency is obtained at the lowest C:H ratio and oxygen content. Both the C:H ratio and oxygen content have almost the same effect on the CGE.

It is interesting to realize that the feedstock having fairly a low syngas HHV (RDF) comes with the highest CGE. The reason can be found in Table 2, where the RDF has the lowest calorific value compared to other feedstocks, resulting in a large CGE. Also over the main part of the domain (Fig. 3), 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. 4. 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%. Although the achievable CCE is feasible through the entire range of C:H ratio and oxygen content (84% and more), using the graph for CGE, one might choose a feedstock with corresponding syngas CGE greater than 70% to have a gasification process economically feasible.

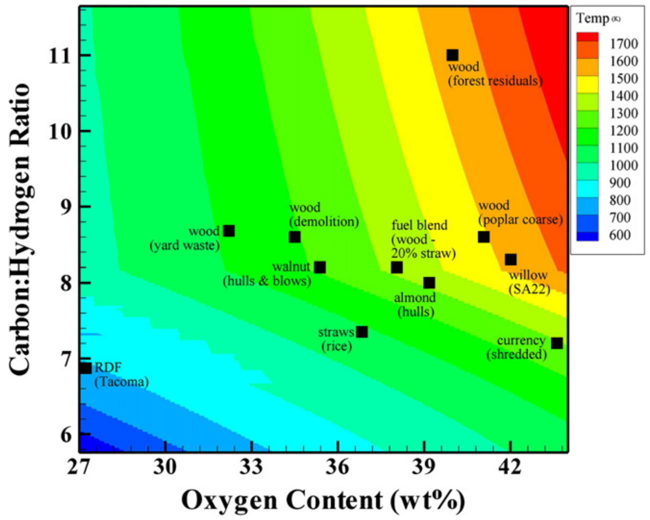

Fig. 5. Variation of the produced syngas temperature (K) based on the C:H ratio and oxygen content of the biomass materials.

Fig. 5 shows the produced syngas temperature distribution for the same variations of the C:H ratio and oxygen content as for the previous figures. The gasification relies on chemical processes at elevated temperatures, e.g. 700 K or higher. As it can be observed, almost through the entire range of oxygen content and C:H ratio, the temperature does not drop below the minimum acceptable level. However, depending on gasifier specifications, some economical/technical concerns might limit the upper achievable temperature during gasification. Therefore, not necessarily all the data presented in this graph is applicable for all gasification purposes, as gasification of materials with a high C:H ratio and oxygen content results in a syngas with fairly high temperatures.

4.2. Practical approaches for biomass selection

In this section, using an example, a practical approach is introduced on how to utilize the figures presented in previous section for selecting appropriate biomass materials for various gasification purposes.

As long as there is no more than one choice of biomass to gasify, the procedure simply consists of choosing the gasifier and appropriate operating conditions. This is the approach followed by majority of gasification researches conducted so far [8,10–13,15,16,18,21,22]. However, not necessarily the above story is true for all gasification cases. Imagine a scenario for which there are more than a few types of biomass to choose from. Here there is a literature gap; where no one has suggested any scientific criteria to facilitate the selection procedure. The present research aims to fill the gap; introducing a new approach in which its novelty is in presenting a set of figures that can be utilized to purposely choose appropriate type of biomass to achieve certain syngas specifications. Provided the approximate/ultimate analysis of the biomass match those of Table 3, and gasifier type and corresponding operating conditions are the same as those considered in this research (downdraft gasifier, atmospheric pressure), then achieving the same results is guaranteed as presented in the figures. To get a better understanding, an example case is studied below to practically tutor how to utilize the figures.

In order to achieve a syngas with the calorific value about 370 MJ/kmol and the temperature below 1200 K, the first approach coming into mind is to randomly select a few biomass materials and gasify them one at a time, in order to evaluate the syngas calorific values and, eventually, choose one feedstock with a calorific value close to the calorific value of interest. Clearly, such a trial and error approach is not only inaccurate, but also time-consuming.

The second approach presented here, is based on the figures produced in this study. Beginning with the HHV plot (Fig. 2), a syngas with a calorific value of 370 MJ/kmol corresponds to a feedstock with 30 to 39 wt.% oxygen content and 7.9 to 8.5 C:H ratio. Referring then to the temperature contours (Fig. 5), to satisfy the above temperature requirement of being below 1200 K, the oxygen content range of the appropriate biomass materials is restricted one more time between 30 and 34.8 wt.%. Having obtained the oxygen content and C:H ratio, one can refer to either biomass materials ultimate analysis tables (see Table 2 or published reports and literature, such as ref.[24]) or an easy-to-use table produced in this study based on the available data (see Table 3) to find the proper feedstock which best meets the syngas calorific value and temperature requirements. Following this approach, it becomes possible to choose the right biomass material for gasification purposes more easily and more accurately, based on the final syngas characteristics, prior to gasification.

4.3. The limitations and extension of the present approach

There are several limitations associated with the present methodology, which need to be considered while trying to follow the proposed approach:

- None of the biomass contaminants including (but not limited to) S, N, Alkalis, and Cl, has been taken into account through numerical modeling. During gasification, neither SOx nor NOx are expected to be produced; nevertheless, there might be some operational/technical concerns regarding these elements, which makes it necessary to be aware of.
- To get comparable results, dry-based ultimate analyses have been considered through the present study. However, in order to get more accurate results, it is recommended to represent the graphs on a dry ash-free basis, which is more common in standardized biomass measurements.
- Because of their simplicity and operator-friendliness, downdraft gasifiers have been chosen as the default type with common operational conditions (see Section 4). However, considering practical scenarios, other types of gasifiers might be more applicable, which might impose extra factors to be accounted for, e.g. melting temperature in fluidized-beds.
- The experimental references used to validate the present numerical algorithm are all utilizing fixed-bed downdraft gasifiers. However, the authors are not able at this point to confirm the applicability of developed graphs for other types of biomass gasifiers.

The authors are trying to modify the present numerical algorithm; include contaminates in equilibrium model, consider other types of gasifiers, extend operating conditions ranges, and involve more biomass materials in the model data library. However, the present paper is fairly capable of presenting a true estimation of the gasification of biomass materials subjected to a given gasifier type and operating conditions, and providing a reliable criterion for choosing appropriate biomass materials to achieve desired gasification products.

5. Conclusion

A new practical approach is presented that can be used in the selection procedure of a proper biomass material for gasification purposes. First using numerical simulation of the gasification process for a wide variety of biomass materials, a series of contours for syngas characteristics are produced. Contours are plotted with respect to the biomass oxygen content and C:H ratio for syngas HHV, CGE, CCE, and temperature. While CGE, CCE, and temperature are mainly affected by biomass oxygen content, the HHV changes mostly under the effect of C:H ratio.

Instead of using a trial and error approach to select a biomass material for gasification purposes, the presented plots in this paper can

Table 3
Classification of various biomass materials based on their oxygen content and C:H ratio.

O 2 C :H	34.5	35.0	35.5	36.0	36.5	37.0	37.5	38.0	38.5	39.0
9.25					Christmas Trees^{a}			Hemlock Bark^{b}		
9.00	Grape Marc^{b}							Urban Wood–Ag^{a}		Pine Bark^{b}
8.75									Alder/Fir Sawdust^{a}	Elm Bark^{b}
8.50	Wood^{a} (Demolition)	Birch Bark^{b}	Wood^{a} (Land Clearing)					Pine Chips^{b}	Beech Bark^{b}	Spruce Bark^{b}
8.25			Walnut^{a} (hulls and blows)	Walnut^{a} (blows)				Wood–Straw Residue^{b}	Bana Grass^{a} (HI, Immature)	
8.00			Mint^{a} (Straw) Rice^{a} (hulls)	Rice^{a} (husks)			Switchgrass^{a} (Columbus, OH)	Wood–20% Straw^{a}	Alfalfa Stems^{a}	Almond^{a} (hulls)
7.75						Pulm Fibres–Huss^{b}	Pepper Plant^{b}		Olive^{b} (Pits)	Reed Canary Grass*
7.50										
7.25		Mixed Waste Paper^{b}				Rice^{a} (straw)				
7.00										
6.75										Groundnut^{b} (shells)
6.5										
6.25										
6.0									Cotton^{b} (husks)	

Table 3 (*continued*)

C:H / O_2	39.5	40	40.5	41	41.5	42	42.5	43	43.5	44
9.25				Hazelnut (shells)[b]						
9.00					Sunflower[b] (husks)	Coconut[b] (shells)			Olive wood[b]	
8.75	Wood–Almond[b]							Pine Sawdust *		
8.50	Urban Wood[a]	Wood – Pit[a]	Furniture Waste[a] Hybrid Poplar[a]	Poplar–Coarse[a] Willow[a] (SA22–Top)	Urban Wood –Ag[a] Wheat[a] (straw–Imperial)	Willow[a] (SP3–1Yr) Willow[a] (SA 22–3Yr)	Fir Mill Waste[a]	Eucalyptus Bark[b]	Willow[a] (SV1–3Yr)	Red Oak Sawdust[a]
8.25		Pine Pruning[b]	Almond[a] (shells)	Walnut (shells)[b]		Willow[a] (SA 22–1Yr) Wheat[a] (straw–CA)	Miscanthus[a] (Sinensis Gracillimus) Wheat[a] (straw–OR) Switchgrass[a] (Dakota Leaf, MN)	Sugar Cane[a] (Bagasse, HI)	Miscanthus[a] (Silberfeder) Sugar Cane[a] (Bagasse–Screened)	Willow[a] (SV 1–1Yr)
8.00				Pistachio[a] (shells)	Barley[b] (straw)	Sorghastrum[a] (Avenaceum) Straw[a] (Wheat-DK)	Willow[a] (SH 3–1Yr)	Arundo[a] (Arundo Bonax)	Willow[a] (SA 22–Butt) Switchgrass[a] (Summer–MM, MN)	Wood[b]
7.75										
7.50			Corn[b] (straw)			Prune[a] (pits)	Rape[b] (straw)			
7.25										
7.00						Buffalo Ground[a] (Albuquerque NM)			Currency[a] (shredded)	Soya[b] (husks)

[a] Ref. [23].
[b] Ref. [24].

be utilized to more easily and more accurately choose a feedstock while being sure that its gasification under given operating conditions results in a syngas with the desired gasification characteristics.

Nomenclature

x,y,z	numbers of atoms of hydrogen, oxygen, and nitrogen per one atom of carbon in the feedstock; respectively
w, m, s	the amounts of water, air, and steam per one kmol of feedstock, respectively
n_i	the number of moles of species i
x	the mole fraction of species i in the ideal gas mixture
v	the stoichiometric number
P^o	the standard pressure (1 atm)
n_{total}	the total number of moles of produced gas
n_j	the stoichiometric coefficients of the complete combustion products
K	equilibrium constant
$\tilde{R}$	the universal gas constant
ΔG°_T	the standard Gibbs function of formation
h°_f	the enthalpy/heat of formation
T	Temperature
Δh°_T	the enthalpy difference between any given state and the reference state
$\bar{C}_p(T)$	the specific heat at constant pressure
C_1,C_2,C_3,C_4,C_5	the coefficients for determining the specific heat
N	the number of gasification products
C, H, O, N, S, and A	carbon, hydrogen, oxygen, nitrogen, sulfur, and ash contents of feedstock, respectively
LHV	lower heating value of the fuel
HHV	higher heating value of the fuel

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