Performance Analysis of a Woodchip Downdraft Gasifier: Numerical Prediction and Experimental Validation

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Abstract: The study deals with a multi-faceted theoretical approach, symbolic, analytical and numerical, based on the chemical equilibrium assumption, addressed at predicting the performance trends of downdraft wood-gasification processes so to assess the optimal ranges of input parameters, in particular the equivalence ratios, suitable to achieving the highest cold gas efficiencies whilst keeping the more the possible tar-free the produced bio-syngas. The time-steady, zero-dimensional model has been developed within MATLAB® (the computing language and interactive environment from Matrix Laboratory) and solved by enforcing the constraints posed by the equilibrium constants in relation to two reactions, gas-water shift and methanation. Particular care is devoted toward verifying the real attainment of the equilibrium condition, as attested by an actual presence of products from the equilibrium reactions together with a zero difference $\Delta E$ between the energy flows entering and exiting the system, an issue often overlooked. With respect to other similar theoretical approaches, the numerical model, assisted by the symbolic counterpart for better interpretation and intrinsic validation of results, shows a distinct advantage in predicting rather accurately the syngas composition for varying gasification temperatures, as attested by cross comparisons with experimental data directly taken on an instrumented, dedicated, small-scale downdraft gasifier operational at DIME/SCL (the Savona Combustion Laboratory of DIME, the Dept. of Mechanical, Energy, Management and Transportation Engineering of Genova University). The behavior of cold gas efficiency clearly points out that, from an energy conversion point of view, the optimal gasification temperatures turn out comprised between 900 °C and 1,000 °C: this range is indeed characterized by the highest concentrations in the energy-rich syngas components CO and H₂. For higher temperatures, as induced by higher air-to-fuel ratios, the progressive oxidation of above components, together with increasing nitrogen levels, would decrease the bio-syngas heat values.

Key words: Downdraft gasifier, woodchip gasification, equilibrium chemistry, MATLAB® simulation.

1. Introduction

The use of renewable energy sources plays an ever increasing role, at all crucial, in energy production, both for the gradual decrease in the availability of fossil resources and, most importantly, for the planetary-scale impact of fossil fuels’ utilization. There are several thermo-chemical conversion processes that can be used for energy generation with a reduced environmental impact, one of the most promising is wood and biomass gasification, because the gaseous fuel (bio-syngas) produced by this process is, when burned in air, by far more environmental friendly than any liquid or solid counterpart. On top of that, the syngas is directly suitable to feed internal combustion engines, both spark ignited and, in dual-fuel mode, also diesel.

Biomass gasification process is, fundamentally, a partial oxidation at temperatures in the range of 800-1,200 °C with the target of producing a gaseous fuel. Unlike the processes of combustion, which aim to a direct conversion “solid-to-heat”, in gasification, the attention is focused on the process “solid-to-syngas”, if the feedstock is biomass and the oxidizer is air, the gaseous mixture produced is mostly made up, in terms of energy-containing components, by carbon monoxide and hydrogen, unavoidably diluted in a large amount of inert nitrogen, up to, and even beyond, 50% in volume. There is also presence of carbon dioxide, water vapor,
methane, and unreacted char and tar. The mixture, traditionally called as producer gas, and more recently bio-syngas, may contain impurities, such as dust, tar, and heavy metals, in addition to the char, so that, before being used, is often cooled, filtered and purified.

The process takes place inside reactors classified according to the geometry and the directions of the internal flows (namely, the feedstock, the oxidizer and the product gases), in which the oxidizing agent may be air, oxygen, steam or a mixture of these. The choice in general is based on the ultimate gas quality desired, the system complexities and related costs, the overall geometry- and energy-scale of the process plant, and, of course, the syngas final utilization, which can involve chemical synthesis, conversion to liquid fuels or to methane, direct combustion in boilers or for heat generation, power production (possibly in cogeneration mode) in internal combustion engines, gas turbines or fuel cells and others, including grid distribution. Interestingly, with combined gasification and synthesis processes (performed in so-called bio-refineries), wood and biomass can be converted quite efficiently into both valuable fuels and useful bio-materials by taking advantage of the on-site co-production of thermal energy, electricity and steam.

Within the above scenario, the objective of this study has been that of setting up and validating, a numerical approach suitable to predict, possibly in parametric fashion, the syngas quality and efficiency of a typical downdraft gasifier, fed with woodchips or properly treated biomass residues. To pursue the said target, it is necessary, as a first step, to clearly define the level of accuracy and detail which is expected from the theoretical model. Several approaches aim to assess just the final composition of chemical equilibrium [1-6], while others, which follow methods based on chemical kinetics, try to distinguish a sequence of zones along the gasifier characterized by different processes [7-10]. As discussed rather thoroughly in Ref. [11], modelizations can be divided into the simpler and more general, thermo-chemical equilibrium approaches and the more complex, but case-specific, kinetic-rate modeling ones. There are also methods which combine both above approaches and even completely different ones, such as those based on neural networks [12, 13].

A well known approach based on chemical equilibrium [14], although now somewhat outdated mainly due to its limits and also to a few apparent inconsistencies, non the less, by careful utilization, seems to succeed, with its related on-line calculator, in assessing with fair accuracy the composition of the syngas. However, the required input impositions of reactor temperature and of final CH\textsubscript{4} concentration, which should be more properly treated as outcome values, appear as limitations of the model. In addition, by so doing, equilibrium is forced to take place anyhow, without verifying if the thermodynamic conditions are consistent with its actual attainment. This latter issue is largely overlooked and seldom addressed. Other known inconsistencies of Ref. [14] come from ill, or null, responses of output to changes in input parameters.

One of the main targets of the present investigation has thus been that of removing above limitations whilst keeping the generality and ease of application of an equilibrium-based approach. The gasification process is herewith modeled by imposing chemical equilibrium via minimization of the Gibbs function while, at the same time, taking into account two reactions, water-gas shift and methanation, and incorporating a double control, mass and energy, on the reactions. In order to reach a more reliable interpretation of results, two different solution algorithms have been developed, one symbolic and the another analytical/numerical. They, solved in MATLAB® environment, succeed in safely calculating the equilibrium temperature of the reactor, checking its real attainment by verifying, in addition to the Gibbs function minimization, the actual presence of products as proof that the reactions have indeed taken place. Moreover, and at difference with other investigations, the detailed temperature dependence of several variables has also been taken into account,
which has been performed by using Nist-Janaf tables (the tables from National Institute of Standards and Technology) [15]. Once equilibrium is verified, the code evaluates the bio-syngas composition and also the energy flows involved in the process. Some relevant results are cross compared with other theoretical investigations as well as with direct measurements performed on a very recent, prototypical and small-size downdraft gasifier operational at DIME (the Dept. of Mechanical, Energy, Management and Transportation Engineering of Genova University).

2. The Complete Model: Chemical, Thermodynamical, Mathematical

The time-steady, zero-dimensional model herewith developed, and then implemented in MATLAB®, is based on the assumption of chemical equilibrium, enforced by satisfying, at atmospheric pressure, the constraints of the equilibrium constants. This assumption has been, in particular for downdraft gasifiers, validated in Ref. [2], wherein it is shown that, both pyrolysis and gasification products, being forced to pass through the hot reduction zone, can actually reach rather quickly the equilibrium condition, at all compatible with the typical residence times of a downdraft process. It is further assumed that the produced gas contains only the following species: CO, H2, CO2, CH4, N2, H2O, with a negligible tar production. Ash and N2 are considered inert.

The global gasification reaction of a general biomass molecule, normalized with respect to one carbon atom, can be written as:

\[ \text{CH}_x \text{O}_y \text{N}_z + m_w (\text{H}_2 \text{O}) + x_{\text{air}} (\text{O}_2 + 3.76 \text{N}_2) \rightarrow x_1 \text{H}_2 + x_2 \text{CO} + x_3 \text{CO}_2 + x_4 \text{H}_2 \text{O} + x_5 \text{CH}_4 + x_6 \text{N}_2 \]

At the left hand side, there are, respectively, one biomass mole, its wetness content and the moles of air, whilst at the right hand side there are six unknowns, represented by the moles of H2, CO, CO2, H2O, CH4 and N2 in the syngas. Notice that, \( x_6 \), i.e., the nitrogen exiting the gasifier, is directly given by the sum of the nitrogen moles in the air and, if any, in the biomass (both deemed as inert).

The molar amount of water for each mole of biomass \( (m_w) \) can be written as:

\[ m_w = \frac{M_b \cdot U}{M_{\text{H}_2 \text{O}}} \cdot 10^3 \]  

where, \( M_b \) is the biomass in input (kg); \( M_{\text{H}_2 \text{O}} \) is the molar mass of water in the biomass (g/mol); \( U \) is the humidity content of biomass.

The moles of inlet air \( (x_{\text{air}}) \) are evaluated from the equivalence ratio \( E_r \), which, for fuel molecules expressed in the form \( C_\alpha H_\beta O_\gamma N_\zeta \), is given by Ref. [5]:

\[ E_r = \frac{\frac{M_{\text{air}}}{M_b}}{\left( \frac{M_{\text{air}}}{M_b} \right)_{st}} = (\alpha + 0.25\beta - 0.5\gamma)(0.3 \div 0.6) \]

where, \( M_{\text{air}} \) is the amount of air in input (kg). By considering that, during the gasification process, the biomass undergoes partial pyrolysis in defect of air, Eq. (3) imposes an equivalence ratio \( E_r \) ranging from 30% to 60% of its stoichiometric value. In order to evaluate the biomass molar composition, reference has been made to Table 1, re-elaborated from Ref. [5]. From this information, it is easy to derive the number of moles of each species component.

In order to evaluate the six unknowns appearing in Eq. (1), the following procedure has been followed. First of all, the elemental mass conservation equations are written as follows:

Carbon:

\[ x_2 + x_3 + x_5 - m_c = 0 \]

Hydrogen:

\[ m_H + 2m_w = 2x_1 + 2x_4 + 4x_5 \]

Oxygen:

\[ m_O + m_w + 2x_{\text{air}} = x_2 + 2x_3 + x_4 \]

Nitrogen:

\[ \frac{m_N}{2} + 3.76x_{\text{air}} = x_6 \]

Eq. (7) says that, nitrogen atoms at exit come directly from the \( N \) content in biomass and in inlet air \( (z/2 + 3.76x_{\text{air}}) \). We can then evaluate the total elemental mass balance:

\[ x_{\text{tot}} = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 \]

The further Eq. (13) required to determine the six
Table 1 Ultimate analysis of several biomasses and their chemical formula.

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Ultimate analysis (%)</th>
<th>( \text{C}<em>\text{H}</em>\text{O}<em>\text{N}</em>\text{Ash} )</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>50.7</td>
<td>6.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Rubber wood</td>
<td>50.6</td>
<td>6.5</td>
<td>0</td>
</tr>
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<td>Eucalyptus</td>
<td>46.04</td>
<td>5.82</td>
<td>0.03</td>
</tr>
<tr>
<td>Dry subabul</td>
<td>48.15</td>
<td>5.87</td>
<td>0.3</td>
</tr>
<tr>
<td>Forest residue chips</td>
<td>51.3</td>
<td>6.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Spruce bark</td>
<td>49.9</td>
<td>5.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Wood chips</td>
<td>51.8</td>
<td>6.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Saw dust (pine)</td>
<td>51.00</td>
<td>6.00</td>
<td>0.08</td>
</tr>
<tr>
<td>Coconut shell</td>
<td>52.00</td>
<td>5.70</td>
<td>0.04</td>
</tr>
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<td>Douglas fir bark</td>
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unknowns are obtained by imposing chemical equilibrium. To this end, the evaluation is performed of the elementary reactions’ equilibrium constants by way of Gibbs free energy minimization. The reactions assumed to take place within the overall gasification process are the following:

**Boudouard reaction:**
\[
\text{C} + \text{CO}_2 \rightarrow 2\text{CO}, \quad (9)
\]

**Water-gas reaction:**
\[
\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2, \quad (10)
\]

**Methane reaction:**
\[
\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4, \quad (11)
\]

By combining Eqs. (9) and (10), as suggested in Ref. [3], the following reaction is obtained:

**Water-gas shift reaction:**
\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2, \quad (12)
\]

Therefore, the equilibrium constants, respectively, for Eqs. (11) and (12), can be written as:
\[
K_1 = \frac{x_\text{CO}_2}{x_\text{CO} \cdot x_\text{H}_2\text{O}}, \quad K_2 = \frac{x_\text{CO}_2 \cdot x_\text{H}_2}{x_\text{CO} \cdot x_\text{H}_2\text{O}}, \quad (13)
\]

The evaluation of \( K_1 \) and \( K_2 \) is now performed by imposing the minimization of Gibbs free energy which, for an ideal gas, is a function of temperature whilst its dependence on pressure is weak [6]. The expression is:
\[
\ln K_i (T) = \frac{-\Delta G^0_{i.T}}{R \cdot T} \quad (14)
\]

with:
\[
\Delta G^0_{i.T} = \sum v_i \cdot \Delta G^0_{f,T, i} \quad i = 1, 2 \quad (15)
\]

where, \( R \) is the universal gas constant equal to 8.314 J/mol*K, \( T \) is absolute temperature (K), \( v_i \) are the stoichiometric numbers, positive for products, negative for reactants \( \Delta G^0_{i.T} \) is standard Gibbs function of the reaction, \( \Delta g^0_{f,T, i} \) is the standard Gibbs functions of formation at \( T \) for each gaseous species \( i \) (values taken from Ref. [15]).

For Reaction (12):
\[
\Delta G^0_{f,1} = \Delta g^0_{\text{O}_2} + \Delta g^0_{\text{H}_2} - \Delta g^0_{\text{CO}} - \Delta g^0_{\text{H}_2\text{O}} \quad (16)
\]

For Reaction (11):
\[
\Delta G^0_{f,2} = \Delta g^0_{\text{CH}_4} - \Delta g^0_{\text{H}_2} \quad (17)
\]

At this point, the values of \( \Delta g^0_{f,T, i} \), calculated for each species at the corresponding temperature, are utilized into Eqs. (16) and (17) so that, by virtue of Eq. (14), the constants \( K_i \) can then be determined. This allows to evaluate the moles of each species by solving the following system:

\[
\begin{align*}
K_1 \cdot x_\text{CO}_2 \cdot x_\text{H}_2 - (x_\text{CO} \cdot x_\text{H}_2\text{O}) &= 0 \\
K_2 \cdot (x_\text{CO}_2)^2 - x_\text{CO} \cdot x_\text{H}_2\text{O} &= 0 \\
x_\text{CO}_2 + x_\text{CO} + x_\text{H}_2\text{O} &= 0 \\
2 \cdot x_\text{CO}_2 &= 0 \\
x_\text{CO}_2 + x_\text{CO} + x_\text{H}_2\text{O} &= 0 \\
x_\text{CO} + x_\text{H}_2\text{O} &= 0
\end{align*}
\]

By taking advantage of MATLAB® environment, two solution methods have been developed and made operative: a symbolic approach and an analytical/numerical one. They both converge to the same results, but in different fashion. In the first approach, symbolic variables are used: their number and type must be declared, specifying if, during iterations, they should assume positive or negative values (in the present case, the unknowns being the molar fractions of syngas components, they have to be always positive). In the numerical approach, the range within which each variable can vary must be specified,
in addition to initial conditions. As a result, the symbolic solution turns out less constrained than the analytical one, and, by taking advantage of the least squares method, it allows to reach more easily the result. On the other hand, the numerical approach follows an analytical way, it is more accurate but not always converges to a unique solution; its run times are longer. The opportunity to have available both solutions yields a remarkable advantage in terms of a more reliable and deeper interpretation of the process under investigation.

In order to solve Eq. (18), it is necessary to know the gasification process temperature, which has been obtained by satisfying the enthalpy conservation constraint: \( H_{\text{reactants}} = H_{\text{products}} \) written as follows:

\[
h_{f,b}^0 + x_{\text{air}} \left( (\Delta h_{T,x_{\text{air}}})_{T_{\text{start}} \rightarrow 298.15} + h_{f,x_{\text{air}}}^0 \right) + m_w \\
+ \left( (\Delta h_{T,m_w})_{T_{\text{start}} \rightarrow 298.15} + h_{f,m_w}^0 \right)
\]

\[
= (\zeta/2 + 3.76 \cdot x_{\text{air}}) \cdot \left[ (\Delta h_{T,N_2})_{298.15 \rightarrow T_{\text{exit}}} + h_{f,N_2}^0 \right] + \\
\sum_{i=1}^{5} x_i \cdot \left[ (\Delta h_{T,i})_{298.15 \rightarrow T_{\text{exit}}} + h_{f,i}^0 \right]
\]

(19)

where, \( h_{f,b}^0 \) is the biomass enthalpy of formation, \( x_i \) is the mole number of each species \( i \), \( h_{f,i}^0 \) is the formation enthalpy of each species \( i \), \( \Delta h_T \) is sensible enthalpy.

Eq. (19) can be more explicitly, reformulated in the following expression, where the heat losses \( Q_1, Q_2 \) (defined shortly below) are also accounted for:

\[
h_{f,b}^0 + x_{\text{air}} (h_{f,O_2}^0 + 3.76 h_{f,N_2}^0) + m_w \cdot \\
(h_{f,H_2O,\text{iq}} + h_{f,H_2O,\text{vap}}) = x_1 (h_{f,H_2}^0 + c_{p,H_2} \Delta T) + \\
x_2 (h_{f,CO}^0 + c_{p,CO} \Delta T) + x_3 (h_{f,CO_2}^0 + c_{p,CO_2} \Delta T) + \\
x_4 (h_{f,H_2O,\text{gas}} + c_{p,H_2O,\text{gas}} \Delta T) + \\
x_5 (h_{f,CH_4}^0 + c_{p,CH_4} \Delta T) + \\
(\zeta/2 + 3.76 x_{\text{air}}) \cdot \\
(h_{f,N_2}^0 + c_{p,N_2} \Delta T) + Q_1 + Q_2
\]

(20)

The reference temperature for the system, corresponding also to the standard temperature for the heat of formation tables, is set at 298.15 K. The temperature changes from this state are indicated with \( \Delta T \). The syngas temperature \( T_{\text{exit}} \) is taken as equal to the gasification temperature. Enthalpy, Gibbs free energy and specific heat of each species are taken from Ref. [15]. The sensible heat \( h_T \) and the formation heat \( h_f \) make up the total enthalpy for reactants and products. For each species \( i \), the following relation holds:

\[
\Delta h_{T,i} = \int_{298.15}^{T} c_p(T) dT
\]

where, \( c_p(T) \) is the constant-pressure specific heat, function only of temperature.

Whilst, the heat of formation of the elements (kJ/kg), such as \( O_2, N_2, H_2 \), is null, that of biomass can be evaluated through its lower heat value \( (LHV_b) \) [5]:

\[
h_{f,b}^0 = LHV_b + \left( h_{f,CO_2}^0 \cdot \frac{1,000}{MM_b} \right) + \\
\left( h_{f,H_2O,\text{gas}}^0 \cdot \frac{1,000}{MM_b} \right) \cdot \frac{x}{2}
\]

(22)

where, \( LHV_b \) (kJ/kg) can be derived from the higher heat value \( (HHV_b) \) through relation:

\[
LHV_b = HHV_b - \left( \frac{x}{2} \cdot \frac{MM_{H_2O}}{MM_b} \cdot \frac{h_{f,H_2O,\text{gas}}^0}{MM_{H_2O}} \right) \cdot 1,000
\]

(23)

Whilst, \( HHV_b \) (kJ/kg) can be evaluated as follows [5]:

\[
HHV_b = (349.1 \cdot C + 1178.3 \cdot H - 103.4 \cdot O)
\]

(24)

As far as the heat losses are concerned, two possible kinds are considered. We call with \( Q_1 \) the loss due to deficiency in thermal insulation, inducing external heat transfer via conduction, convection and radiation. They are here assumed as 3% of biomass \( HHV_b \). There is also a heat loss \( Q_2 \) due to char formation, taken as 2% of biomass \( HHV_b \). The heat losses are thus formulated as follows:

\[
Q_1 = 3\% \cdot HHV_b \cdot \frac{MM_b}{1000}
\]

(25)

\[
Q_2 = 2\% \cdot HHV_{\text{char}} \cdot \frac{MM_b}{1000}
\]

(26)

In order to finally reach the value of the gasification temperature, corresponding to the attainment of the
equilibrium condition, it is necessary to bring to zero the difference $\Delta E$ between all the energy flows entering and exiting the system:

$$\Delta E = h_{f,b}^0 + m_w \cdot (h_{f,H_2O}^{s} + h_{vap}) + x_{air}(h_{f,O_2}^0 + 3.76 h_{f,N_2}^0) - x_1(h_{f,H_2}^0 + c_{p,H_2} \Delta T) - x_2(h_{f,CO}^0 + c_{p,CO} \Delta T) - x_3(h_{f,CO_2}^0 + c_{p,CO_2} \Delta T) - x_4(h_{f,H_2O,gas}^0 + c_{p,H_2O,gas} \Delta T) - x_5(h_{f,CH_4}^0 + c_{p,CH_4} \Delta T) - (x/2 + 3.76 x_{air}) \cdot (h_{f,N_2}^0 + c_{p,N_2} \Delta T) - Q_1 - Q_2$$

(27)

Once, by virtue of the converging iterations of the solution algorithm, $\Delta T$ is arrived at, the exit temperature is obtained from:

$$\Delta T = T_{exit} - 298.15$$

(28)

The numerical code is named “Biosyn”, exactly as the new gasifier technology herewith presented shortly below. The parametric results achieved with the software Biosyn greatly helped during the phases of design, development and performance analysis of the hardware counterpart. Code Biosyn, with a proper graphical interface, is going to be made soon available, for online open-access executions and sharing of results, on dedicated website: www.biosyn.it.

3. Experimental Investigation

For validation purposes, in the next paragraph, the results achieved with the model above discussed will be compared with some relevant corresponding outcome obtained from another modeling approach. In addition to that, in order to compare theoretical results with ad-hoc experimental data, advantage has been taken of the availability of two small scale prototypical downdraft gasifiers, property of Tecnoforest Ltd., now undergoing performance testing at the laboratory DIME/SCL of the University of Genova. The syngas generator, registered as Biosyn, is fully operational and its main functional parameters are continuously monitored via a control panel and a dedicated computer.

With a consumption of biomass (at 25% humidity) of about 23 kg/h, it generates 19 kW of electric power and 43 kW of thermal power. Contrarily to other similar-class equipment, such as the GEK (gasifier experimenter’s kit) gasifier manufactured by the company ALL Power Labs, USA, Biosyn does not require to use the hot discharge from the internal combustion engine to assist the pyrolysis phase within the reactor, letting the entire discharge heat from the engine available for cogeneration purposes. A “market-ready” version of Biosyn gasifier is pictured in Fig. 1 together with, on the right, the connected genset. Fig. 2 shows several views of the provisions and instrumentation utilized for taking syngas samples at gasifier exit. During these investigations, a Biosyn “laboratory” version was used, pictured in Fig. 3: the reactor is on the front, the syngas filter (in blue paint) is behind, the biomass barrel on the top. Notice that the flare is visible because the gasifier is operating.

For assessing the gasifier operational parameters and performing the analysis of syngas components, in addition to on-line measurements, gas samples were taken for different operating conditions and then accurately analysed off-line. For $N_2$, a continuous analyzer was utilised, for $O_2$, a continuous analyzer equipped with electro-chemical cell was used (following EPA, Environmental Protection Agency, protocol n. 3A 1989), for $CH_4$ and $CO_2$, a continuous FTIR (Fourier transform infrared) analyzer was adopted.

![Fig. 1 Complete Biosyn genset in operation at DIME/SCL.](image-url)
corresponding to “wood chips” in Table 1, and a moisture content of 30%, a parametric analysis has been performed by executing code Biosyn for varying equivalence ratios $E_r$. The output syngas components’ molar concentrations are plotted in Fig. 4. By increasing $E_r$, the oxidation processes are enhanced, so that the gasification temperatures go up, as shown in Fig. 5. The syngas molar composition as a function of temperature is then presented in Fig. 6. Notice that, as

5. Results: Comparisons and Discussion

By specifying in input the biomass composition (same EPA protocol as above), for H$_2$, a GC-TCD (gas chromatography-thermal conductivity detector) analyzer was employed, whilst for CO, a Horiba analyzer was used (following protocol UNI EN 15058:2006, issued by UNI, Italian Norm Unification Agency). Some relevant results of the syngas analyses are reported in the next paragraph (see below), in order to compare them with the corresponding theoretical predictions.

Fig. 2 Instrumentation, provisions and operations for on-line and off-line syngas sampling and testing.

Fig. 3 Biosyn “laboratory” version at DIME/SCL

Fig. 4 Syngas molar composition for varying equivalence ratios $E_r$. 
expected, the optimal syngas composition, in terms of energy-rich CO and H\textsubscript{2} species, is reached for \( E_r \) values ranging from 0.4 to 0.45: lower values are incompatible with an actual attainment of equilibrium \((T < 870 \, ^\circ C)\), which typically corresponds also to unacceptably high levels of tar within the syngas.

In correspondence of the optimal value \( E_r = 0.43 \), for increasing moisture content in the wood, Fig. 7 shows the corresponding decrease of syngas heat values mainly, as can be seen in Fig. 8, due to increasing H\textsubscript{2}O and decreasing CO contents within the gas.

![Fig. 5](image1.png)  
Dependence of gasification temperature on equivalence ratio \( E_r \).

![Fig. 6](image2.png)  
Syngas molar composition for varying gasification temperatures.

![Fig. 7](image3.png)  
Dependence of syngas heat values for varying levels of wood moisture content.

![Fig. 8](image4.png)  
Dependence of syngas composition for varying levels of wood moisture content.
In order to assess validity of the numerical results obtained by application of Biosyn code, Fig. 9 presents some cross comparisons with corresponding predictions taken from Ref. [5]. In order to do that, the syngas composition, in y-axis, had to be converted to kmol of gas component per kmol of biomass whilst, in x-axis, the kmol of air are referred to one kmol of biomass.

The significant differences in results that show up between the two theoretical approaches are attributable to several reasons, among which the most important is deemed to be the following. The model developed in the present study is based on the evaluation of two equilibrium constants, $K_1$ and $K_2$, which respectively refer to Eq. (12) (water-gas shift reaction) and to Eq. (11) (methane reaction): notice that, Eq. (12) is already a “combined” reaction, made up of Eqs. (9) and (10). The model of Ref. [5], instead, solves three equilibrium reactions, i.e., Eqs. (9), (11) and (12), but, in doing so, the relative influence of CO-producing Boudouard Reaction (Eq. (9)) may become excessive, being it already taken care of in Eq. (12). This is motivation for the high CO-concentrations, and correspondingly low CO$_2$-levels, shown in Fig. 9 by Ref. [5], predictions in relation to Biosyn’s. On the other hand, the trends appear correctly predicted by both approaches for varying equivalence ratios.

Finally, on the base of Biosyn results presented in Fig. 10, the gasifier CGE (cold gas efficiency) could be evaluated by applying the definition:

$$CGE = \frac{HHV_{product~gases}}{HHV_{feedstock}}$$  \hspace{1cm} (29)

By introducing the heat values of the energy-containing product gases (H$_2$, CO and CH$_4$), the expression of CGE becomes [5]:

$$CGE = \frac{283,300 x_3 + 283,237.12 x_4 + 89,000 x_5}{HHV_{feedstock}}$$  \hspace{1cm} (30)

which allows to calculate cold gas efficiency in function of gasification temperature as presented in Fig. 11. The trend shown by CGE, which decreases with increasing temperatures, confirms the role played by CO and H$_2$: both these species, that are the major contributors to the syngas heat value, and thus also to the efficiency of the process, are progressively

![Fig. 9 Cross comparisons of Biosyn code results with numerical predictions.](image-url)
oxidated to CO₂ and H₂O as more air is introduced in order to increase gasification temperatures. In doing so, also the concentration of inert nitrogen goes up inducing further decrease in syngas heat value. As expected, CGE decreases with temperature due to exactly the same reasons, but it would not be safe to operate at gasification temperatures below 900 °C due to high tar concentrations within the syngas. This problem, not captured by equilibrium analyses, is indirectly pointed out by the increase in CH₄ for decreasing T, it can be said that, lower temperatures promote formation of hydrocarbons, both light as methane, and heavy as tars.

6. Conclusions

A theoretical approach, based on chemical equilibrium assumption, has been presented which appears suitable to analyze downdraft gasification processes so to predict the trends of performance.
parameters and to assess the optimal operational conditions. More than showing extensive parametric results for wide variations in input variables, what is typically performed in similar studies often without checking if the attainment of the equilibrium condition is really consistent, the emphasis is here placed on assessing the reliability of predictions by comparisons with other theoretical approaches and with experimental data obtained on a dedicated small-scale gasifier. The analytical/numerical model, within the constraints of zero-dimensionality and chemical equilibrium, succeeds in correctly capturing the basic operational features of downdraft gasifiers as attested by experimental comparisons. With respect to other similar theoretical approaches, it shows a distinct advantage in predicting rather accurately the syngas composition for varying gasification temperatures, which is attributable both to a proper selection of the equilibrium reactions avoiding redundancies, as well as to a careful check of real attainment of equilibrium for each single thermo-chemical situation along the performance curve.

The behavior of cold gas efficiency clearly points out that, from an energy conversion point of view, the optimal gasification temperatures appear comprised between 900 °C and 1,000 °C, this range is indeed characterized by the highest concentrations in the energy-rich syngas components CO, H₂. Higher temperatures, corresponding to higher air-to-fuel ratios, would be induced by the progressive oxidation of above components with the syngas heat values getting lower due to increasing levels of inert species CO₂, H₂O and N₂. On the other side, for temperatures decreasing below about 950 °C, as attested by well known experimental evidence, the appearance of heavy pyrolytic hydrocarbons (tars) within the syngas becomes more and more pronounced, hindering its practical utilization as a fuel for internal combustion engines. Interestingly, numerical predictions based on equilibrium hypothesis, an assumption definitely ill-tuned for treating pyrolytic situations, non the less, succeed in “detecting” somehow the presence of unreacted hydrocarbons at the lower gasification temperatures by pointing out increasing concentrations of methane, to be interpreted as the precursor of other, heavier, hydrocarbons.

References


Performance Analysis of a Woodchip Downdraft Gasifier: Numerical Prediction and Experimental Validation


