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Thermodynamic methodology to support the selection of feedstocks for decentralised downdraft gasification power plants

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ABSTRACT

Thermodynamic criteria as a feedstock selection tool for decentralised downdraft gasifiers coupled to spark-ignition engines are presented in this work. The methodology consists of an energy and exergy analysis of gasification process. The analysis is carried out by computational modelling of the gasification process as a function of biomass type (ultimate analysis, moisture content and heating value) and fuel/air ratio. Considering a system operating with different wood species, analysed parameters are gas heating value, energy and exergy efficiencies and engine fuel quality (EFQ). With a fixed fuel/air ratio (2.6) and moisture content (20%wt), it is highlighted that as the carbon-oxygen molar ratio of wood decreases from 2.0 to 1.78 as model input, reaction temperature increases by 9%, energy and exergy efficiencies diminish by 1.8% and 4.2%, respectively, while EFQ increases by 3.2%. Therefore, for decentralised power plants, biomass should be selected to produce higher EFQ.

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Energy; exergy; engine fuel quality; feedstock selection methodology; downdraft gasification; biopower plant

1. Introduction

The selection of biomass as feedstock for biopower plants (gasification process coupled to spark-ignition engines) is a function of several parameters, such as silvicultural variables of forest biomass (energy crops), chemical characterisation, biomass moisture content, heating value, ash content and physical properties such as bulk density and even biomass genetic criteria (Tanger et al. 2013). Also, direct selection of biomass can be made by taking into account waste biomass available as a by-product from agriculture or forestry processes.

Currently, the selection of feedstock as fuel for bioprojects is based on biomass physicochemical properties, such as moisture and ash contents, which impact the performance of the system, but it is difficult to estimate the effect of feedstock on the overall efficiency of power plants. Several studies have been conducted to study the downdraft biomass gasification process in function of biomass properties. Through experimental tests, the effect of biomass physicochemical properties on process performance has been analysed and comparisons between different solid biomass and operating conditions have been conducted under thermodynamic analysis (Lenis and Pérez 2014; Lenis, Osorio, and Pérez 2013; Ruiz et al. 2013; Sharma 2009).

Rao et al. (2004) developed an exergy balance for an updraft fixed-bed gasifier using three sources of biomass. The thermodynamic study showed higher energy and exergy efficiencies for biomass with higher carbon-oxygen (C/O) molar ratio and lower moisture content.

Dutta et al. (2014) studied the effect of biomass type and moisture content on the downdraft gasification process. They highlighted that low heating value of producer gas (LHV_{pg}) decreases with biomass moisture content due to lower combustible gases concentration. From an exergy point of view, exergy destruction increases with biomass moisture content (Pellegrini and de Oliveira 2007). Through a thermodynamic analysis using a chemical equilibrium model, Karamarkovic and Karamarkovic (2010) concluded that exergy efficiency (ExE) of the gasification process increases if the process is fed with dry biomass or by preheating processes.

By means of an equilibrium model, Jarunghammachote and Dutta (2007) studied downdraft gasification of municipal solid waste (MSW). They found that the concentration of gaseous fuel in producer gas (PG), temperature, LHV_{pg} and ExE decrease with biomass moisture content. The second law efficiency decreases due to higher dilution of combustible gases (CO, H₂ and CH₄) in N₂. This is due to higher amount of air required to reach a temperature (1073 K) that maintains the auto-thermal conditions of the process.

Azzone, Morini, and Pinelli (2012) characterised the gasification process of agricultural wastes by using a chemical equilibrium model. It is highlighted that LHV_{pg} decreases as biomass carbon content decreases (ultimate analysis). Zhang et al. (2011) analysed the biomass gasification process using four types of biomass materials under auto-thermal conditions. By means of a chemical equilibrium model, the authors found that PG energy and exergy increase as carbon in the ultimate analysis increases, but their First and Second laws of Thermodynamics efficiencies decrease.

Ghassemi and Shahsavan-Markadeh (2014) studied biomass gasification performance through a sensitivity analysis of process parameters (gasifying agent, type and moisture of biomass) with an equilibrium model. The model was adjusted to predict the formation of tars and char as by-products. Regarding the ultimate analysis, cold gas efficiency (CGE) decreases as the C/O molar ratio increases and, regarding the gasifying agent (oxygen-enriched air), LHV_{pg} increases with lower N₂ concentrations in the oxidant.

Ptasinski, Prins, and Pierik (2007) studied the gasification processes of different solid biofuels by means of an equilibrium model. It was found that fuels with higher oxygen content require less amounts of air to reach the highest carbon conversion efficiency. Therefore, with less air involved in the reaction, temperature, CO, H₂ and ExE decrease. Tapasvi et al. (2015) studied the effect of torrefied biomass on the gasification process through numerical simulations with an equilibrium model. The oxygen-carbon (O/C) ratio decreases with the torrefaction process; therefore, energy and exergy efficiencies increase when the pretreated biomass is gasified.

Biomass selection for gasification processes was considered by Vaezi et al. (2012). They developed a methodology to select biomass materials as a function of gasification process conditions and uses of PG. The methodology is composed of an equilibrium model that simulates the gasification process as a function of biomass ultimate analysis (carbon-hydrogen molar ratio between 5.8 and 11.6 and oxygen mass concentration 27–43%wt). The model calculates output parameters, such as first law efficiency, LHV_{pg}, carbon conversion efficiency, temperature and equivalence ratio. It is highlighted that CGE, carbon conversion efficiency and gasification temperature increase with biomass oxygen content.

In this paper, a methodology to select biomass as fuel for low-medium gasification power plants coupled to spark ignition (SI) engines (<1.0 MWe) is developed. The proposed methodology integrates the analysis of First and Second laws of Thermodynamics and PG quality for fuel for SI engines. This approach to select biomass to use its PG as engine fuel has not been found in the cited literature. The approach constitutes a contribution to the selection process of biofuels as feedstock for bioenergy projects in order improve the overall ExE of biopower plants.

2. Methodology

In this paper, a methodology to select wood as feedstock to produce bioenergy by means of a gasification process coupled to SI ignition engines is proposed. The methodology is developed through a

complete thermodynamic analysis of the gasification process as a function of biomass type (ultimate analysis and moisture content) and fuel/air ratio. Response variables taken into account are CGE, ExE (total, chemical and physical) and engine fuel quality (EFQ). Biomass selection as a function of PG quality for engine fuel contributes to reducing the global irreversibilities of a power plant. This is due to higher irreversibility of SI engines with regard to the biomass gasification process (Ptasinski, Prins, and Pierik 2007; Sezer, Altin, and Bilgin 2009).

The work's methodology integrates an extended gasification model under thermochemical equilibrium as described in detail by Melgar et al. (2007) and a new model validation with experimental results from a biomass gasification plant at industrial full scale. Finally, the model is used as a computational tool to carry out the thermodynamic analysis. The aim is to analyse the effect of biomass by taking into account that PG will be burned in four-stroke spark-ignition engines.

2.1. Model description

The model presented in this work has been extended by adding an exergy submodel to analyse the gasification process from the thermodynamic point of view. Detailed description of the initial approach is presented by Melgar et al. (2007). The model combines chemical and thermodynamic equilibrium of the global reaction. It predicts the final composition of the PG as well as the reaction

Table 1. System equations of the thermodynamic model.

Thermochemical equilibrium model	Equation
$CH_mO_pN_qS_r + wH_2O + x(O_2 + 3.76N_2) \rightarrow$ $\dots aCO + bCO_2 + cH_2 + dCH_4 + eH_2O + fN_2 + gO_2 + ISO_2$ $\therefore x = \frac{1}{F_{ig}F_{st,bms}}$	(1)
$C + 2H_2 \leftrightarrow CH_4$ $\therefore K_1 = \frac{(P_{CH_4}/P_0)}{(P_{H_2}/P_0)^2} = \frac{dn_T}{c^2}$	(2)
$CO + H_2O \leftrightarrow CO_2 + H_2$ $\therefore K_2 = \frac{(P_{CO_2}/P_0)(P_{H_2}/P_0)}{(P_{CO}/P_0)(P_{H_2O}/P_0)} = \frac{bc}{ae}$	(3)
$ExE = \frac{Ex_{output}}{Ex_{input}}$ $ExE_{ch} = \frac{Ex_{ch,pg}}{Ex_{input}}$ $ExE_{ph} = \frac{Ex_{ph,pg}}{Ex_{input}}$ $\therefore Ex_{output} = Ex_{pg}$ $\therefore Ex_{input} = Ex_{bms} + Ex_{H_2O} + Ex_{air}$ $\therefore Ex_i = Ex_{ch,i} + Ex_{ph,i}$	(4)
$Ex_{pg} = Ex_{ch,pg} + Ex_{ph,pg}$	(5)
$Ex_{pg} = \sum n_i \cdot E_i^0 + \sum n_i \cdot \int_{T_0}^{T_k} C_{p,i} \left(1 - \frac{T_0}{T}\right) dT$	(6)
$Ex_{bms} = (LHV_{bms,db} + 2442 \cdot h) \cdot \lambda_{db} + 9417 \cdot S$	(7)
$\lambda_{db} = \frac{1.0438 + 0.1882 \cdot \left(\frac{H}{C}\right) - 0.2509 \cdot \left(1 + 0.7256 \cdot \left(\frac{H}{C}\right)\right) + 0.0383 \cdot \left(\frac{N}{C}\right)}{1 - 0.3035 \cdot \left(\frac{O}{C}\right)}$	(8)
$Ex_{air} = n_{air} \sum E_j^0$ $\therefore Ex_{air} = n_{air} (E_{O_2}^0 + 3.76E_{N_2}^0)$	(9)

temperature. Therefore, with PG composition, a range of thermodynamic parameters can be derived, such as CGE, LHV_{pg} , EFQ of the PG and thermodynamic second law efficiency (ExE). The main model equations (1–9) are presented in Table 1.

By means of the substitution fuel formula ($C_nH_mO_p$), specific molecular weight of biomass, molar quantity of water per mol of biomass, stoichiometric air/fuel ratio and formation enthalpy of biomass can be determined (Melgar et al. 2007). Global reaction of the downdraft biomass gasification process considered in the model is presented in Equation (1). Reaction products and PG composition are based on chemical equilibrium among the different species, taking into account that, in downdraft gasifiers, content of tars in the final gas can be neglected (Melgar, Pérez, and Horrillo 2009; Mendiburu et al. 2014; Vaezi et al. 2012). Residence time of biomass in the gasifier is long enough to assume that the carbon content of biomass is gasified; thereby, char formation as a by-product is neglected (Erlich and Fransson 2011; Vaezi et al. 2012). To solve the system, two reactions in equilibrium are added. In the reduction zone of the gasifier, hydrogen is reduced with char to produce methane (see Equation (2)). Equilibrium constant K_1 relates the molar amount of species involved. The second auxiliary reaction is the water–gas shift reaction, which describes the equilibrium between CO and H_2 in the presence of water (Equation (3)). The PG is modelled as an ideal gas, and the reactor operates at atmospheric pressure.

2.1.1. Exergy efficiency

ExE calculation is defined as the ratio between exergy leaving the gasifier, that is, PG exergy, and exergy fed to the gasifier, that is, biomass, moisture and air (see Equation (4)) (Zhang et al. 2011). Exergy is composed of two terms: chemical and physical exergy (Jarungthammachote and Dutta 2007). PG exergy is presented in Equations (5) and (6), where n_i is the number of moles of each gaseous species of the PG and E_i° is the standard exergy of each gaseous species of the PG (Kotas 2012). Physical exergy integrals of the gaseous species are determined by means of Janaf tables (Melgar et al. 2007); T_o is the reference state temperature (298 K).

According to Kotas (2012), wood biomass exergy can be determined by means of its ultimate analysis, moisture content (mass fraction) and LHV in a dry base. Hence, exergy for wet wood fuels is calculated by Equations (7) and (8).

In this work, the gasification process simulated considers dry air as a gasifying agent due to the fact that most low-medium power plants with downdraft gasifiers use air as a gasifying agent (Pérez et al. 2012). Therefore, the model considers that reactants enter at ambient conditions, which means that air physical exergy is zero ($Ex_{ph,air} = 0$). Hence, gasifying agent exergy is calculated by means of Equation (9). Standard exergy of gaseous species is taken from Kotas (2012).

2.1.2. Engine fuel quality

As described above, the power plant configuration consists of a gasifier and a PG conditioning system coupled to four SI engines. According to Tinaut et al. (2006), the effective power of an engine (kW) can be estimated as follows (see Equation (10)).

$$\dot{N}_e = K_D \cdot K_o \cdot EFQ \quad (10)$$

K_D and K_o parameters are a function of engine design and operating conditions, respectively. These parameters are constant for a stationary engine in a power plant, while EFQ directly affects engine power because it is a function of PG composition, which is affected by biomass composition, LHV_{bms} and gasification conditions. EFQ is a function of gaseous fuel–air stoichiometric ratio ($F_{stq,pg}$), air mole fraction in the PG–air mixture and LHV_{pg} (Tinaut et al. 2006) (see Equation (11)).

$$EFQ = LHV_{pg} \cdot Y_{air} \cdot F_{stq,pg} \quad (11)$$

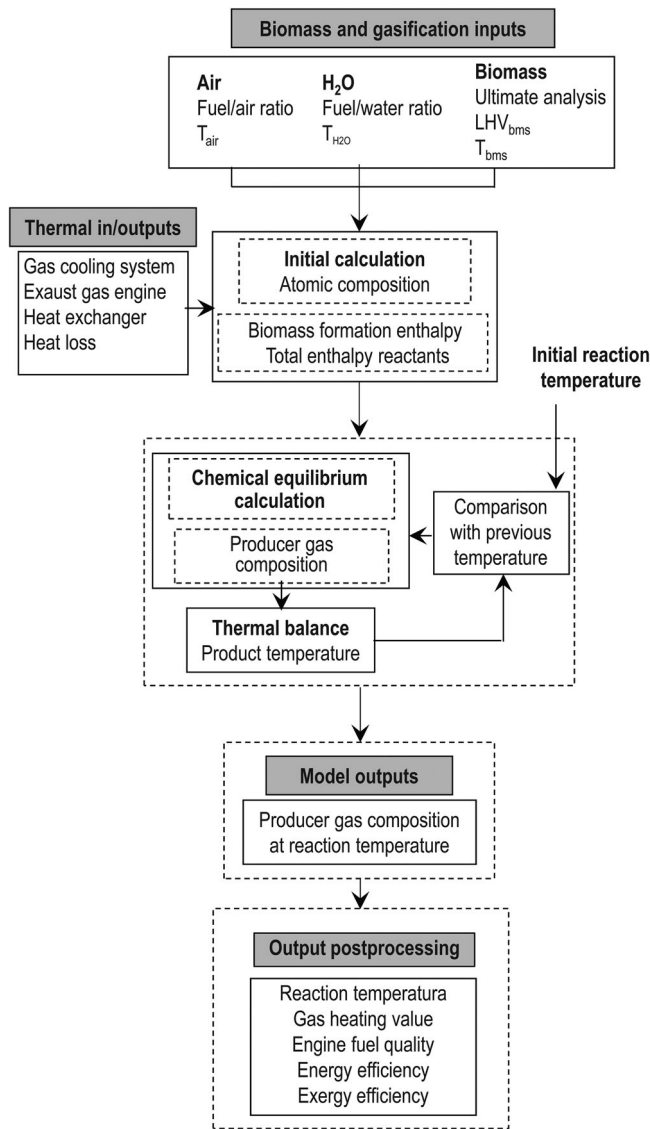


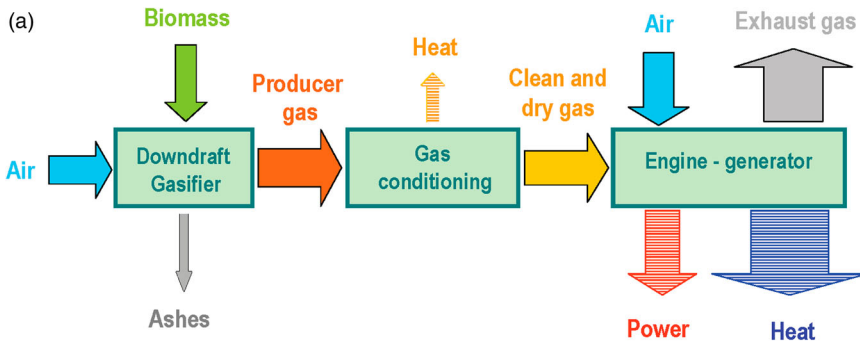
Figure 1. Block diagram of thermodynamic methodology.

$F_{stq,pg}$ is the stoichiometric gas fuel–air ratio of the engine intake mixture, and it is calculated from gaseous fuel composition (kg_{pg}/kg_{air}). Y_{air} is the air molar fraction that is fed to the engine in the mixture PG–air, $Y_{air} = n_{air}/n_{mix}$. A detailed description of EFQ is presented by Tinaut et al. (2006).

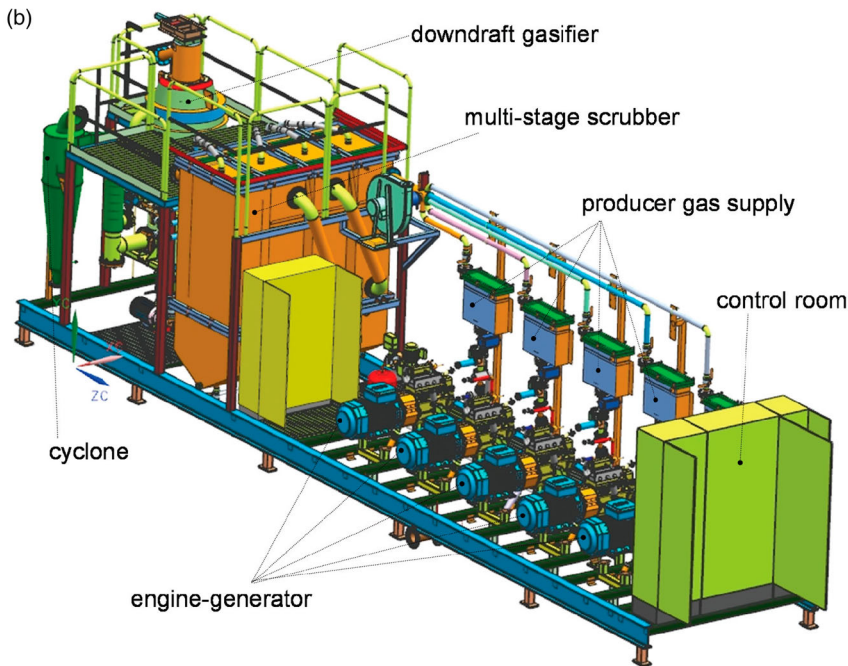
2.1.3. Structure of the methodology

In Figure 1, it is shown the block diagram that describes the thermodynamic methodology. In the first stage (biomass and gasification inputs), with moisture and ultimate analysis of biomass is calculated the substitution formula of biomass and molar quantity of water. Real air molar quantity is calculated from fuel/air equivalence ratio; moreover, total enthalpy of reactants is estimated.

In the second stage, PG composition is calculated by the Newton–Raphson method to solve the non-linear equations system. Subsequently, reaction temperature is calculated equalising the enthalpy of reactants (biomass, moisture and air) and products (PG). The calculated temperature



Flow diagram of power plant



Full scale power plant demonstration

Figure 2. Systems of the biomass gasification power plant (100 kW_e).

is the input for the next iterative calculus of PG composition until the chemical and thermal equilibria are reached. Therefore, thermodynamic parameters that characterise the thermochemical process are calculated with final PG and biomass compositions (ultimate analysis and heating value).

2.2. Biomass power plant based on gasification

A biomass power plant produces 100 kW_e of power and about 200 kW_{th} of thermal power with specific fuel consumption between 0.9 and 1.1 kgk W_e⁻¹ h⁻¹ with 10%wt of biomass moisture content. The plant configuration consists of three subsystems: an atmospheric downdraft fixed-bed gasifier, a syngas conditioning stage and a power generation system (engine-generator) (Figure 2).

The gasifier is a downdraft fixed-bed reactor with a heat exchanger and geometry variation as a function of bed length (height of 1.7 m and internal diameter between 0.25 and 1.0 m). The upper

Table 2. Average performance data of the power plant under steady state.

Parameter of energy behaviour	Average value
Biomass consumption rate (kg/h)	98–100
Air flow (kg/h)	303.5
PG mass flow (kg/h)	385
$T_{\text{out Gasifier}}$ (°C)	522
LHV_{pg} (kJ/Nm ³)	5045
F_{rg} (fuel/air ratio)	2.2
Thermal power (kW)	377
Electric power (kW _e)	94.3
Cold gas efficiency (CGE) (%)	85

part of the gasifier is composed of a stainless steel cylindrical body. The lower part of the gasifier (pyro-combustion chamber) is composed of two straight circular cones, which are welded at their largest diameter. After the cones, the bed is agitated by a rotating grate. At the gasifier bottom, there is an ashtray and a line that conducts PG to the heat exchanger followed by a gas conditioning system. Clean gas is used to fuel four internal combustion engines.

The gas conditioning system is composed of a cyclone and a multistage scrubber. The aim of this subsystem is to eliminate particulate matter, water and other components that could damage the engines, such as tars, as well as to decrease gas temperature.

The generation subsystem is composed of four reciprocating internal combustion engines (four-stroke spark-ignition engine) coupled to electric generators.

The thermochemical equilibrium model is validated against experimental data obtained in a test under steady state conditions (see section 3.1). Steady state data were recorded during approximately 5:40 h:min. The test was carried out with pine wood chips with 12.94%wt of average moisture ($\text{CH}_{1.2629}\text{O}_{0.5857}$, $\text{LHV}_{\text{db}} = 19,565$ kJ/kg). Average performance of the gasification plant under steady state is shown in Table 2. For this behaviour, it is highlighted that the gas yield reached is $3.9 \text{ kg}_{\text{pg}}/\text{kg}_{\text{bms}}$, and specific fuel consumption is $1.05 \text{ kgk W}_e^{-1} \text{ h}^{-1}$ considering a thermal efficiency of 25% for SI engines (Knoef 2012; Payri and Desantes 2011; Pérez et al. 2012).

Figure 3 shows flow, composition and heating value of the PG; it also shows temperature at the gasifier outlet. Flow is measured by an orifice plate device, and gas composition is measured (O_2 , N_2 , CO_2 , CO , H_2 and CH_4) by a gas chromatograph, *VARIANT MicroGC*. The test was conducted from 9:58:28 to 19:10:34. The gasification process reaches temperature and flow stable conditions at

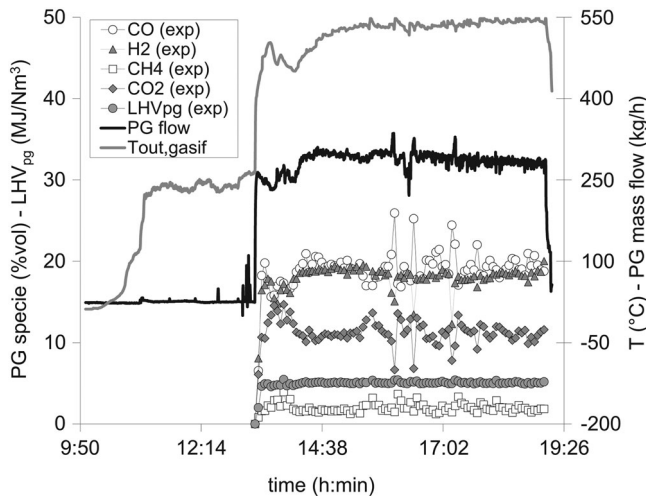


Figure 3. Mass flow and composition (CO , H_2 , CH_4 and CO_2) of PG and temperature at the gasifier outlet during the experimental test.

around 13:18:12; therefore, the data used to validate the model are from 13:26:24 to 19:06:21, giving a total of 5 h and 40 min of test time under steady state conditions. In this period of time, three significant CO, H₂ and CO₂ points of change are highlighted. These composition changes occur at 16:04, 16:27 and 17:12 h. CO changes from 19%vol. to 25.2%vol., while H₂ and CO₂ decrease from 18%vol. to 13.6%vol. and 11%vol. to 7.1%vol., respectively. This is due to the larger amount of char involved in the reaction regarding fresh biomass feedstock. If there is a higher amount of char, fixed carbon in the reaction increases and CO production is favoured. It can be observed that CO diminishes to average concentrations when fresh biomass feedstock is supplied to the reactor; this stabilises the thermochemical process.

Biomass consumption, CGE of the gasification process and fuel/air ratio are calculated by a diagnostic model based on measurements of composition and mass flow of PG (Melgar, Pérez, and Horriillo 2009).






2.3. Wood fuels analysed

Quality of a useful biomass as feedstock for a gasification process is a function of its bulk density, chemical composition, heating value, moisture and ash content (Lenis, Osorio, and Pérez 2013). In Colombia, there is plenty of wood biomass that can show good performance as fuel for bioenergy projects. In this paper, forest species with highest potential as energy crops in Colombia are selected, taking into account silvicultural aspects.

Forest crops with potential as energy are based on identifiable, measurable and consistent criteria regarding the reality of the forestry sector in Colombia. The analysed criteria are planted area, yield and harvest time. It is expected that the species with higher planted area (ha), higher yield or mean annual increment (MAI, m³/ha/year) and lower harvest time (years) are more suitable for bioenergy projects because a sustainable biomass supply is ensured (Del Valle, Restrepo, and Osorio 2014). The main forest species analysed in this work are *Acacia mangium* (AM) (11,300 ha, 28 m³/ha/year, 4 years), *Eucalyptus grandis* (EG) (46,115 ha, 25 m³/ha/year, 7 years), *Gmelina arborea* (GA) (4972 ha, 23 m³/ha/year, 7 years), *Pinus patula* (PP) (38,495 ha, 20 m³/ha/year, 13 years) and *Pinus maximinoi* (PM) (59,811 ha, 20 m³/ha/year, 13 years) (Del Valle, Restrepo, and Osorio 2014).

Chemical characterisation of the selected forest species is presented in Table 3. Average ultimate analysis of wood species and their C/O molar ratios are presented with standard deviation (STDEV) because these variables are important input parameters for biomass selection methodology.

Table 3. Chemical characterisation of the wood fuels (\pm standard deviation).

	Woody biomass				
	PM	PP	EG	AM	GA
					
Solid fuel properties					
Proximate analysis (%wt d.b.)					
Volatile matter	74.33	72.57	67.35	73.25	72.00
Fixed carbon	25.46	27.17	32.34	26.46	27.24
Ash	0.22	0.26	0.31	0.29	0.77
Ultimate analysis (%wt daf)					
C	54.84 (± 0.23)	55.70 (± 0.58)	53.68 (± 0.02)	53.35 (± 0.37)	53.37 (± 0.13)
H	7.09 (± 0.84)	7.13 (± 0.13)	6.79 (± 0.85)	6.75 (± 0.07)	7.04 (± 0.47)
O	38.06 (± 1.07)	37.18 (± 0.68)	39.53 (± 0.83)	39.90 (± 0.30)	39.59 (± 0.33)
C/O molar ratio	1.92 (± 0.06)	2.00 (± 0.06)	1.81 (± 0.04)	1.78 (± 0.03)	1.80 (± 0.01)
LHV _{daf} (kJ/kg)	19,031.26	19,154.45	19,083.07	18,759.44	18,896.09
F _{stq,bms} (kg _{bms} /kg _{air})	0.1427	0.1401	0.1486	0.1401	0.1477
Substitution formula (daf)	CH _{1.552} O _{0.521}	CH _{1.573} O _{0.501}	CH _{1.517} O _{0.552}	CH _{1.519} O _{0.561}	CH _{1.584} O _{0.556}

Differences in elemental composition are evident due to the low STDEV found; therefore, conclusions about the effect of ultimate analysis of biomass on the thermodynamic characterisation of the gasification process are valid.

3. Results and discussion

In this section, model validation with experimental data and sensitivity analysis to select forest wood biomass as feedstock for power generation by means of thermodynamic parameters is presented. Analysed variables as a function of biomass composition and fuel/air ratio are CGE, ExE, ExE_{ch}, ExE_{ph} and EFQ. The methodology proposed can be used with different kinds of feedstocks. Wood materials (resource with high-energy potential) studied in this work are considered as an example to validate the model and methodology.

3.1. Model validation

The parameters used to validate the model as a computational tool to predict the thermodynamic performance of an industrial gasifier are composition of PG, fuel/air ratio (F_{rg}), LHV_{pg} and CGE.

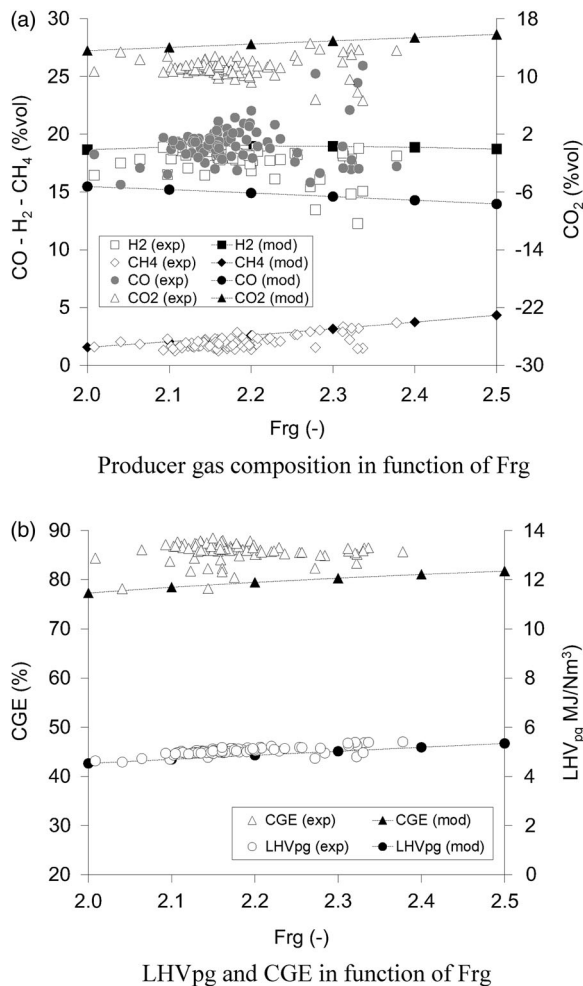


Figure 4. Validation of the model under thermochemical equilibrium by means of data from an industrial downdraft gasifier.

Simulations were carried out as the function of chemical composition, moisture content and LHV of the biomass and the fuel/air ratio of the process reached in the power plant (2.0–2.5).

Figure 4 shows a comparison between experimental data (exp) and model response variables (mod). A good agreement can be observed between the experimental parameters and the ones estimated by the model. These results validate the model as a computational tool under its hypotheses.

Numerical results tend to underestimate CO concentration, while CO₂ is overestimated. On the other hand, CH₄ has a slight trend to be overestimated, and H₂ is slightly underestimated. The behaviour shown by the model is due to the auxiliary equations approach (Equations (2) and (3)). While fuel/air ratio increases, reaction temperature decreases and favours the water–gas shift reaction where CO reacts with steam to produce CO₂ and H₂. And, at the same time, equilibrium constant for H₂ reduction with char is activated; therefore, production of CH₄ is favoured, and H₂ decreases. Thereby, the model tends to slightly underestimate LHV_{pg} and CGE.

It is highlighted that the model adequately predicts the trends of the experimental global variables as a function of fuel/air ratio (F_{rg}) under auto-thermal conditions. As the process is fuel rich, the combustible gases increase, and this leads to higher LHV_{pg} and CGE.

Model accuracy is quantified using the root mean square deviation (RMSD) or root mean square error (RMSE) between model results and experimental data. This parameter has been used to validate gasification models in previous studies (Barrera, Salazar, and Perez 2014; Jarungthammachote and Dutta 2007; Mendiburu et al. 2014; Vaezi et al. 2012). Units of the RMSD are the same as the ones used by each variable compared. Therefore, average RMSEs of the model are $RMSD_{CH_4} = \pm 1.36\%vol.$, $RMSD_{H_2} = \pm 0.75\%vol.$, $RMSD_{CO} = \pm 4.71\%vol.$, $RMSD_{CO_2} = \pm 3.3\%vol.$, $RMSD_{LHV_{pg}} = \pm 0.21 MJ/Nm^3$ and $RMSD_{CGE} = \pm 5.79\%$. The comparison shows a good model behaviour to simulate the biomass gasification process at the industrial scale under auto-thermal and steady regimes. Therefore, the model will support wood biomass selection as feedstock under thermodynamic analysis for power generation by means of biomass gasifiers coupled to SI engines.

3.2. Effect of fuel/air ratio and biomass moisture content

Once the thermochemical model is validated with experimental data from an industrial downdraft gasifier, the effect of biomass moisture content (0–40%wt) and fuel/air ratio (1.8–3.0) on PG composition and thermodynamic parameters is studied. Simulation results are not presented in this work due to the similarities with previously published studies in which pine bark moisture content and fuel/air ratio were studied (Melgar et al. 2007). However, the main findings of this work with different forest wood biomass materials are presented.

3.2.1. Cold gas efficiency

For the five species tested, energy efficiency of the gasification process increases as relative fuel/air ratio increases and with decreasing biomass moisture content. This behaviour is similar for the five wood biomass types due to the similitude in terms of elemental composition and heating value. Process efficiency increases when moisture content decreases due to lower amount of water in the process. This leads to a higher reaction temperature, which favours CO and H₂ formation (Sharma 2009).

Additionally, there is a proportional relation between the fuel/air ratio and CGE because as the combustion is more incomplete (higher fuel-rich conditions), a higher amount of gases with energy content is produced; this leads to producing a PG with higher heating value and, therefore, a better thermodynamic first law efficiency.

Higher values of CGE are in the range of 80% considering adiabatic conditions for all forest species. This is due to the similar heating value of the five investigated wood species. These yields are achieved with a high relative fuel/air ratio ($F_{rg} > 3.0$) where moisture does not affect the process. These operating points, with a higher fuel/air ratio and higher moisture contents (>30%wt), are thermodynamically unstable under an auto-thermal perspective (Caton et al. 2010). Therefore, registered

CGE is about 70% with restriction in moisture content at values between 25%wt and 30%wt (Erlich and Fransson 2011; Melgar et al. 2007).

3.2.2. Exergy efficiency

ExE is calculated using physical and chemical exergy from reagents and products under adiabatic conditions. This efficiency estimates the process irreversibility associated with wood thermochemical processing into a combustible gas using air as a gasifying agent in low-medium power plants.

Lower irreversibility is reached with higher F_{rg} and lower moisture contents. However, reaching fuel/air ratios higher than 3.0 is difficult when air is used as the gasifying agent (Centeno et al. 2012; Erlich and Fransson 2011; Garcia-Bacaicoa et al. 2008; Martínez et al. 2011; Rao et al. 2004). From the exergy point of view, it is concluded that biomass must be fed to the gasification plant in as dry a condition as possible and the process must be conducted at the highest fuel–air ratio without losing its auto-thermal state. In typical fuel/air ratios of gasification processes, $2.0 < F_{rg} < 3.0$, ExE varies between 80% and 90%; this means that the irreversibility associated with the downdraft gasification process (adiabatic conditions) is around 20% and 10%, respectively.

3.2.3. Engine fuel quality

A typical application of downdraft gasifiers is for electricity generation with engines at medium power. Melgar et al. (2007) stated that EFQ measures energy density from the stoichiometric mixture (PG–air) to be fuelled in SI engines. It is highlighted that these are the suitable power machines for lower-middle powers from 10 to 1000 kW_e (Larson 1998; Martínez et al. 2012; Mendiburu et al. 2014).

In order to maintain PG quality within optimal values (EFQ \geq 1500 kJ/kg), 25%wt is the maximum permissible moisture content of any of the five forest species. At higher moisture contents, CH₄ concentration in the PG increases, and CO and H₂ diminish. Higher CH₄ requires higher amounts of air to burn gaseous fuel under stoichiometric conditions in SI engines. This leads to a lower energy density of the mixture to be fed to the SI engine.

According to experimental data from the gasification plant (section 3.1), typical F_{rg} values of gasification plants are between 2.0 and 3.0; this leads to producing a gas quality between acceptable values (EFQ \geq 2000 kJ/kg). Therefore, for any wood species, it is concluded that it should be fed to the gasifier with a maximum moisture content of 25%wt; moreover, the power plant must work with F_{rg} values between 2.0 and 3.0 or higher if the process is to be auto-thermally stable (Erlich and Fransson 2011; Melgar et al. 2007).

3.3. Effect of biomass type on thermodynamic parameters

In this section, thermodynamic parameters are shown as a function of F_{rg} and biomass type (see Figures 5–7). In the graphs, solid biofuels are parameterised as a function of their C/O molar ratio (ultimate analysis) and LHV_{bms} in descending order as follows (C/O molar ratio/LHV_{bms} in MJ/kg): PP (2/19.15), PM (1.92/19.03), EG (1.81/19.08), GA (1.8/18.9) and AM (1.78/18.76).

Moisture content of all biomass materials was fixed at 20%wt in order to achieve a real and good performance of the gasification process (Erlich and Fransson 2011; Vaezi et al. 2012). Figure 5 shows reaction temperature, gas composition and LHV_{pg}. Process analysis is conducted for typical fuel/air ratios of the gasification process in downdraft gasifiers, $1.8 < F_{rg} < 3.0$ (Martínez et al. 2012; Yasuaki et al. 2011).

3.3.1. Reaction temperature

Figure 5(a) shows that reaction temperature diminishes with higher LHV_{bms}. This is due to the relation between wood composition and its energy content; LHV_{bms} increases with biomass C/O molar ratio. As biomass C/O increases, the stoichiometric biomass–air ratio ($F_{st,bms}$) decreases (see Table 3). This means that the amount of biomass burned per mass unit of air in stoichiometric conditions diminishes. Therefore, lower $F_{st,bms}$ leads to a lower real biomass/air ratio; this is because

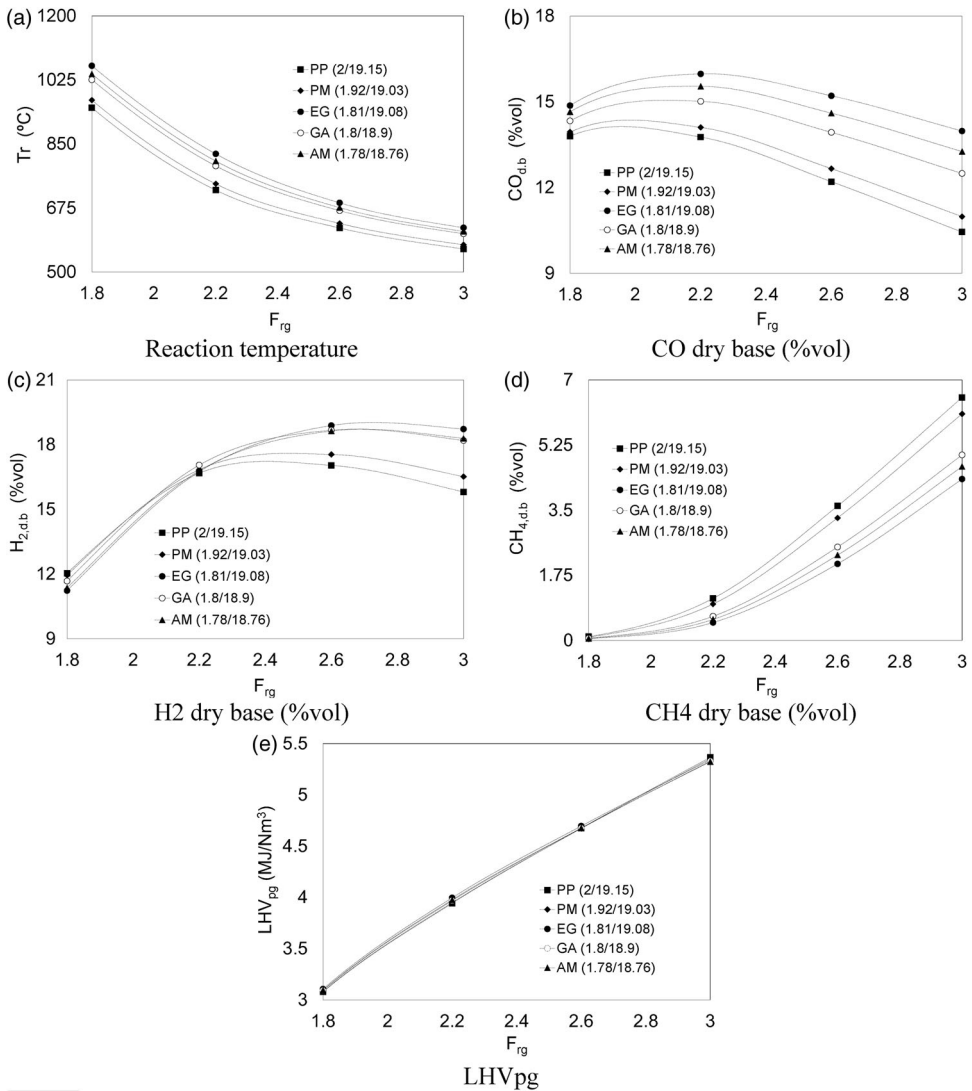


Figure 5. Gaseous fuels concentration in the PG composition and LHV_{pg} as a function of the biomass/air ratio and biomass type (C/O molar ratio/LHV_{bms} in MJ/kg).

a larger amount of air is required to reach a given value of F_{rg} . Equation (1) calculates the real molar quantity of air (x) in the process as a function of fuel/air ratio and biomass/air stoichiometric ratio. A higher amount of air in the gasification process (with higher C/O) leads to an increase in N₂ in the PG. This inert gas is heated by a fraction of the energy released in the exothermic phase of the thermochemical process; therefore, process temperature decreases. Ptasinski, Prins, and Pierik (2007) highlighted that fuels with higher oxygen content require less air to achieve a specific coal conversion efficiency under gasification processes.

According to Equations (2) and (3), equilibrium constants (K_1 for hydrogen reduction with char and K_2 for water-gas shift reaction) are affected by temperature. Therefore, there is a direct effect of biomass composition on PG; this is due to a lower reaction temperature with a higher C/O ratio, so equilibrium constants K_1 and K_2 increase. These equilibrium constants as a function of temperature are presented in Sharma (2008).

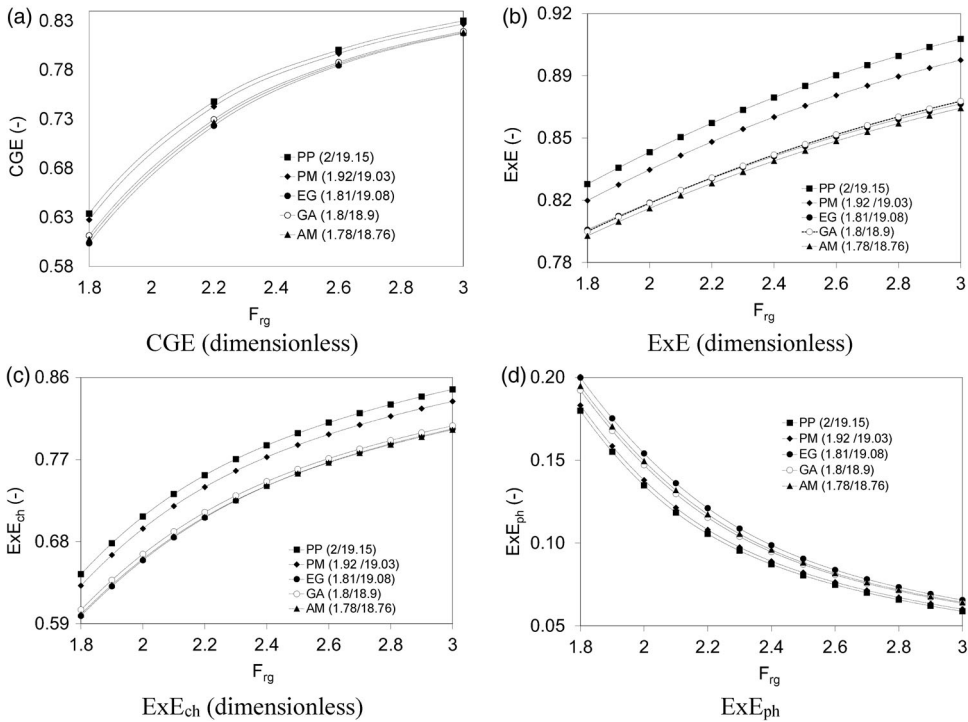


Figure 6. Energy and exergy efficiencies of the gasification process as a function of biomass/air ratio and biomass type (C/O molar ratio/LHV_{bms} in MJ/kg).

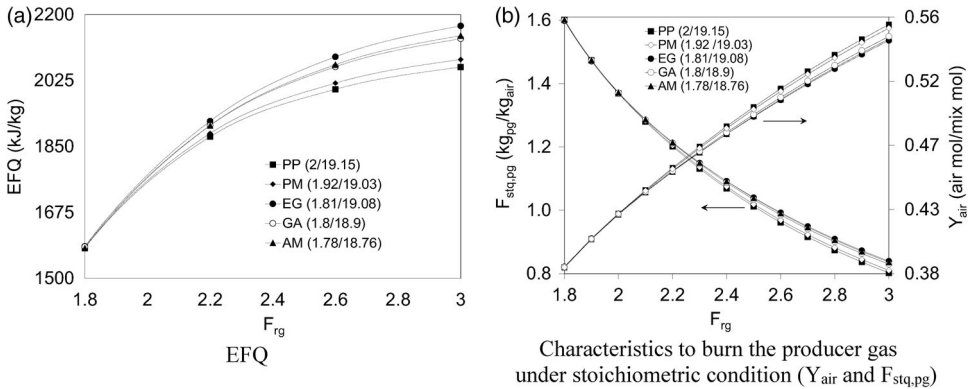


Figure 7. PG specification as fuel for SI engines and its combustion parameters under stoichiometric conditions as a function of biomass/air ratio and biomass type (C/O molar ratio/LHV_{bms} in MJ/kg).

3.3.2. PG composition

Figure 5(b) shows that the CO concentration in PG decreases with a higher wood C/O ratio. CO reacts with steam (water–gas shift) to favour H₂ and CO₂ production (Figure 5(c)). Furthermore, reaction reduction of H₂ with char is activated, favouring CH₄ formation (Figure 5(d)). This explains why, at higher C/O ratios or higher LHV_{bms}, a lower reaction temperature (T_r) is achieved; this leads to lower CO and H₂ concentration while CH₄ increases.

Figure 5(b–d) also shows the effect of F_{rg} on PG composition. As the overall reaction is fuel rich (higher F_{rg}), temperature decreases. Therefore, it is observed that CO decreases as it reacts with steam to produce H_2 . Moreover, H_2 is reduced with char to produce CH_4 . This reaction mechanism explains how woods (PP and PM) that produce higher CH_4 concentrations have lower CO and H_2 concentrations.

From another point of view, it can be seen that woods with lower C/O ratios (more oxygenated biomass materials) reach higher reaction temperatures by involving a lower N_2 quantity in the process. Higher T_r favours CO and H_2 formation in the overall reaction (Equation (1)), and equilibrium constants decrease, reducing CH_4 formation by the reduction of H_2 with char.

3.3.3. Low heating value of PG

Regarding LHV_{pg} , no significant differences were observed as a function of biomass type. This is because biomass materials with higher CH_4 concentration have lower CO and H_2 concentrations, and vice versa (Figure 5(e)). Therefore, if the thermodynamic selection criterion for wood biomass as feedstock for bioenergy projects is LHV_{pg} , there is no difference among the wood species studied because their PG heating value is very similar.

3.3.4. Gasification process efficiencies

CGE, ExE and ExE_{ch} are presented in Figure 6(a–c). All of them show the same trend; efficiencies increase when C/O or LHV_{bms} increases. This is related to process temperature and thus to PG composition. Wood efficiencies (energy and exergy) as a function of F_{rg} in descending order are $PP > PM > GA > AM > EG$. Efficiencies increase with C/O ratio due to lower reaction temperature, which favours CH_4 formation by reduction of H_2 with char. Highest CH_4 concentration in the PG increases energy and exergy of the PG.

According to Equation (4), ExE takes into account PG, biomass and air chemical and physical exergies. Thereby, Figure 6 shows both exergy efficiencies (ExE_{ch} and ExE_{ph}) to analyse the process availability (Figure 6(c) and 6(d)).

ExE_{ph} increases with reaction temperature. At higher reaction temperature regarding the dead state ($T_o = 298$ K), higher energy to develop work is available (Vaezi et al. 2012). According to Figure 6(b), ExE is affected by ExE_{ch} in a higher proportion because PG chemical exergy represents between 70% and 95% of the total exergy, while physical exergy (temperature) represents between 30% and 5%. Considering that power plants with SI engines use PG as fuel to be burnt in engines, chemical exergy is more important than thermal exergy. Thermal exergy can be used in cogeneration processes (Ptasinski, Prins, and Pierik 2007).

Figure 6(a–c) shows that CGE, ExE and ExE_{ch} increase with F_{rg} . If F_{rg} varies from 1.8 to 3.0, efficiencies increase as follows: CGE 23.3%, ExE 8.5% and ExE_{ch} 24%. This is due to combustible gases increasing (CO, H_2 and CH_4) as the process is more fuel rich.

If the selection criteria of wood biomass as solid biofuel for gasification plants are thermodynamic first and/or second law efficiencies (CGE, ExE or ExE_{ch}), biomass material must be selected with higher C/O ratio or higher LHV_{bms} ; these wood specifications allow to reach higher CH_4 concentrations. This is consistent with the results from previous gasification works that studied the effect of fuel type on the gasification process under energy and exergy analysis (Azzone, Morini, and Pinelli 2012; Dutta et al. 2014; Tapasvi et al. 2015; Vaezi et al. 2012).

3.3.5. Engine fuel quality

If the selection criterion of wood biomass is to use PG as fuel in naturally aspirated SI engines, EFQ should be analysed (Tinaut et al. 2006). It is highlighted that EFQ shows an opposite effect with regard to CGE, ExE and ExE_{ch} as a function of wood biomass type (see Figure 7(a)).

EFQ increases with a lower C/O ratio or lower LHV_{bms} . This means that the PG quality for engines is improved when wood biomass with higher oxygen content is used as feedstock. To analyse

this behaviour, it should be noted that SI engines are volumetric machines, and the combustion reaction occurs close to stoichiometric conditions (Sezer, Altin, and Bilgin 2009; Tinaut et al. 2006).

Gasification temperature increases with a higher oxygen concentration in the biomass (lower C/O ratio); this is due to lower amount of N₂ involved in the gasification process. Therefore, higher temperature favours CO and H₂ formation (Sharma 2009). In descending order, EFQ as a function of wood biomass is EG > AM > GA > PM > PP.

As can be seen in Figure 7(a), for a fixed F_{rg}, EFQ decreases with higher C/O ratio (higher LHV_{bms}); this behaviour is due to PG stoichiometric combustion characteristics in the engine. The amount of PG that can be burned per unit of stoichiometric air (F_{stq,pg}) decreases when CH₄ concentration in the gas increases. This leads to LHV of the mixture fed to the engine. Therefore, higher EFQ should be reached to optimise the mechanical variables of the engine, looking to increase its energy and exergy efficiencies (Sezer, Altin, and Bilgin 2009; Tinaut et al. 2006).

In Figure 7(a), the effect of F_{rg} on EFQ is also shown. As the process is more fuel rich (from 1.8 to 3.0), this leads to higher combustible gases concentration and higher LHV_{pg}. Therefore, higher LHV_{pg} increases EFQ by around 25% (see Equation (11)). However, regarding combustion parameters in SI engines, F_{stq,pg} diminishes due to higher amount of air required to burn PG under stoichiometric conditions (see Figure 7(b)).

3.3.6. Process behaviour as a function of biomass type at fixed values of fuel/air ratio and moisture content

Figure 8 shows a thermodynamic analysis summary as an energy selection tool of forest biomass as feedstock for decentralised power by means of the downdraft gasification process. Evolution of the process as a function of biomass type is presented for fixed values of F_{rg} (2.6) and biomass moisture

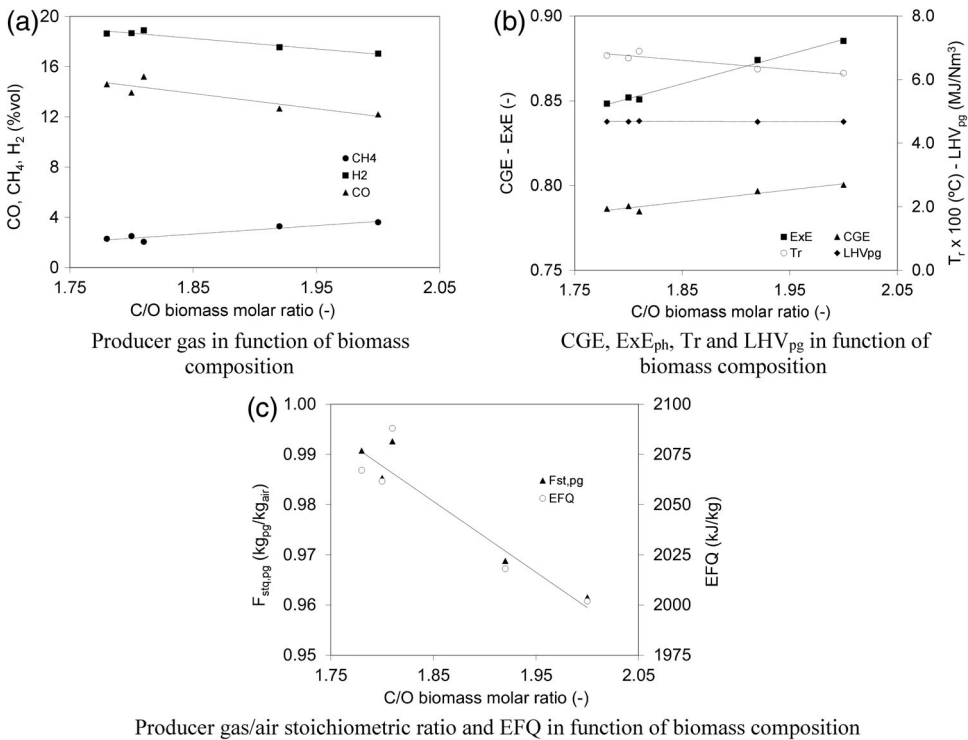


Figure 8. Effect of wood biomass composition on the gasification process and PG combustion parameters under constant F_{rg} = 2.6 and a biomass moisture content of 20%wt.

content (20%wt); both are typical values of the downdraft biomass gasification process under auto-thermal conditions (Martínez et al. 2012; Zhang et al. 2011). A moisture content of 20%wt was selected in order to reach an adequate gasifier performance (Melgar et al. 2007).

Figure 8 shows the thermodynamic parameter variations of the gasification process as a function of biomass composition (C/O molar ratio). When biomass C/O molar ratio decreases from 2.0 to 1.78 (11% reduction), reaction temperature increases by 9%; CH₄ decreases by 36.5%; H₂ and CO increase by 9.4% and 19.6%, respectively; LHV_{pg} does not vary significantly and CGE and ExE decrease by 1.8% and 4.2%, respectively, while EFQ increases by 3.2%.

If the selection criterion of wood biomass for power plants is EFQ, a biomass able to provide a PG–air mixture in stoichiometric conditions with higher energy density should be selected. Therefore, a biomass with a lower C/O molar ratio (higher oxygen content, %wt) must be selected. This was previously discussed. Lower C/O ratios of biomass lead to lower amount of air in the thermo-chemical process to reach a given F_{rg} value (lower x , see Equation (1)). With lower N₂ quantity in the process, reaction temperature increases, promoting CO and H₂ formation, while CH₄ production decreases by a lower K₁ constant value (Sharma 2008).

With a lower CH₄ concentration in the PG, less air is needed to burn the gaseous fuel under stoichiometric conditions inside SI engines (F_{stq, pg} increases). Therefore, the engine can burn a greater amount of PG per unit of air, leading to an improvement of EFQ, and thus the engine power increases (Tinaut et al. 2006). If less air is required for the gasification process to achieve a specific F_{rg} (biomass with lower C/O ratio), the engine also requires less stoichiometric air to burn PG. Therefore, a higher amount of stoichiometric fuel in the volumetric machine will increase its power and decrease its irreversibility.

The thermodynamic parameter to select biomass for gasification projects coupled to internal combustion engines is EFQ and not CGE or ExE efficiencies. Gasification ExE increases with higher CH₄ concentration in the gas, but fuel quality decreases when the amount of air required to burn the PG stoichiometrically in the engine increases. Therefore, biomass materials should be selected as feedstock by sustainable models and the criterion of higher EFQ.

4. Conclusions

Trends and significant changes in the gasification process are found as a function of biomass composition. Therefore, biomass selection criteria for low-medium power plants that operate with downdraft gasifiers coupled to spark-ignition engines are proposed.

Moisture content and fuel/air ratio investigated by means of sensitivity analysis show a clear effect on the biomass gasification process. If biomass moisture content increases, process temperature decreases, inhibiting gasification reactions and thus reducing energy and exergy process efficiencies.

The maximum admissible biomass moisture content is 25%wt; at this moisture level, PG reaches acceptable levels to burn gaseous fuel in SI engines at an EFQ higher or equal to 1500 kJ/kg. LHV_{pg} increases with fuel/air ratio; however, this parameter can increase until the auto-thermal state is maintained.

The gasification thermodynamic parameters analysed to select the biomass as feedstock for bio-energy projects are LHV_{pg}, CGE, ExE_{ch} and EFQ. If LHV_{pg} is the selection criterion, wood biomass type is irrelevant since this parameter does not change significantly. If the highest first and/or second law efficiencies are the selection criterion, biomass must have the highest C/O molar ratio or LHV_{bms}. These wood characteristics will produce a PG with higher CH₄ concentrations; this will favour first and second law efficiencies of the gasification process.

EFQ stands out as an exceptional thermodynamic property to evaluate the thermodynamic performance of biomass and use PG as engine fuel. This is because internal combustion engine performance improves due to higher heating value of the stoichiometric PG–air mixture. Wood biomass types with higher EFQ are biofuels with a lower C/O molar ratio because their PG reaches lower CH₄ concentrations. With a lower biomass C/O molar ratio, the amount of N₂ involved in the

gasification process decreases for a given F_{rg} . This lower concentration of N_2 leads to a higher reaction temperature; therefore, the global gasification reaction favours CO and H_2 production. These two gaseous fuels improve PG quality as fuel for SI engines. Therefore, the mechanical power increases and the irreversibility of the volumetric heat machine diminishes.

Nomenclature

a	mol of CO per mol of biomass
b	mol of CO_2 per mol of biomass
C	mass fraction of carbon
c	mol of H_2 per mol of biomass
C/O	carbon/oxygen molar ratio of the biomass [-]
d	mol of CH_4 per mol of biomass
e	mol of H_2O per mol of biomass
E	energy [kJ]
Ex	exergy [kJ]
E°	standard exergy [kJ/kmol]
f	mol of N_2 per mol of biomass
F_{rg}	gasification fuel/air ratio
$F_{stq,bms}$	stoichiometric biomass/air ratio
$F_{stq,pg}$	stoichiometric producer gas/air ratio
g	mol of O_2 per mol of biomass
h	relative moisture of biomass
h_f°	enthalpy of formation [kJ/kmol]
K	equilibrium constant
K_D	parameter in function of engine design [$m^3 \text{ stroke rev}^{-1}$]
K_o	parameter in function of engine operating conditions [$\text{rev kg m}^{-3} \text{ s}^{-1}$]
l	mol of SO_2 per mol of biomass
M	molecular weight [kg/mol]
Ne	Break power of the internal combustion engine [kW]
n_i	mol <i>i</i> th component of producer gas
n_T	total mol of producer gas
O	mass fraction of oxygen
P	Pressure (kPa or bar)
T	temperature [K or °C]
w	H_2O molar fraction in biomass
x	real molar quantity of air
Y_{air}	engine air molar fraction
Greeks	
λ	ratio between chemical exergy and net calorific value of biomass
Subscripts	
ad	adiabatic
bms	biomass
cg	cold gas
ch	chemical
daf	dry-ash-free conditions
db	dry base
e	engine
ex	exergy
exp	experimental data
i	gaseous species
m	H atoms substitution formula
mix	producer gas–air mixture
mod	numerical simulation result
n	C atoms substitution formula
o	reference or dead state
p	O atoms substitution formula
ph	physical
q	N atoms substitution formula

r S atoms substitution formula
 stq stoichiometric ratio

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Disclosure statement

No potential conflict of interest was reported by the authors.

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