ENERGY PERFORMANCE OF THE BIOMASS GASIFICATION PROCESS

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In this paper the biomass gasification process has been analyzed taking into account the thermodynamic constraints and considering the inherent limits of some possible small-scale processes. A multiphase thermodynamic equilibrium approach has been used to estimate the gas composition and the yield of char for partial oxidation and steam gasification. To obtain a reliable estimate of the thermal efficiency of a real process, a global analysis taking into account the whole balance of plant has been performed, supplementing the chemical equilibrium thermodynamic analysis used for the reacting stages with an evaluation of the enthalpy and exergy fluxes arising from the other plant components.

Keywords: biomass, gasification, cogeneration.

1. Introduction

The renewed interest in the gas production technologies arises from the opportunity of using biomass as feedstock, i.e. a potential substitute for fossil fuels. In this context, one of the most important issues the researchers are focusing on is the exploitation of this renewable energy source by means of sustainable processes and power generation technologies, in order to achieve environmental compatible solutions that can satisfy the increasing power demand. In particular the utilization of synthesis gases at low calorific values (LCV gas) in traditional internal combustion (IC) gas engines (Otto or Diesel cycles) is an interesting option, given the high performances reached by this type of power generators. In this paper it has been considered a typical cogeneration set for combined heat and power (CHP) production, based on a quite simple IC gas engine plant configuration, suitable for small-scale stationary applications.

2. Layout description

The syngas production section consists of a fixed bed gasification reactor heated by a burner. The gasification process is endothermic, as it is carried out with water steam as gasifying agent (steam gasification) and the heat necessary to

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sustain the reactions and to produce the water steam (i.e. the gasifying agent) is supplied by the coupled burner in which a fraction of the produced syngas is oxidized. For the thermochemical conversion process spruce sawdust has been chosen as feedstock, characterized by the following [1]: ultimate analysis (mass fractions, dry ash free basis) 51.58%C, 5.90%H, 42.43%O, 0.08%N, 0.01%S; moisture (mass fractions, wet basis) 8.25%; ash (mass fractions, wet basis) 0.90%.

The considered plant configuration (see par. 4) represents a simple syngas utilization in an internal combustion gas engine. The produced synthesis gas is piped through a clean-up section to the engine, in order to produce electrical energy. The flue gas from the coupled burner and the exhaust gas from the engine are also subjected to a clean-up process and then piped to the chimney after being heated in order to reach the desired temperature. All the plant stages operate at atmospheric pressure. In order to obtain combined heat and power (CHP) production, thermal energy recovery is performed on the engine exhaust gases and on the syngas stream (before entering the clean-up module). The presence of by-products in the syngas makes it necessary to clean-up the gaseous flow before its use by the power generation section. There are different syngas clean-up processes, depending on the feedstock, on the thermal conversion process and on the power generators demand. Internal combustion gas engines have the advantage of higher tolerance to contaminants than gas turbines or fuel cells [2], in particular the tar content can be up to 50-100 mg Nm^{-3} in the producer gas. The usual gas purification arrangement for a biomass plant (wet system) has been adopted for the syngas and the flue or exhaust gases clean-up, including a cyclone, a bag filter and a scrubber [3,4,5]. In the simulations, the clean-up system global energy consumption has been estimated to be 3×10^{-3} kWh Nm^{-3} (specific value relevant the gas subjected to the purification treatment).

The produced syngas stream feeds a 290kWel internal combustion gas engine (conventional alternative Otto cycle). The thermal and electrical efficiencies have been assumed respectively at 38.9% and 46.7% and, for the exhaust gas temperature, a value of 140°C has been chosen.

Table 1

Adopted parameters for the syngas utilization section

Plant unit	*Process parameter*	*Value*
IC gas engine	Temperature syngas (in)	30°C
	Temperature exhausts (out)	140%
	ER, Equivalence ratio	1
	Electrical power	286 kW
	Thermal power	347 kW
	Total displacement	16.6 lt
	Thermal efficiency	46.7%
	Electrical efficiency	38.9%

These values, used in the simulations, are in agreement with the real life engine performances (GE-Jenbacher, 2006 [6]) operating as CHP generation sets.

The syngas LHV suitable for IC gas engine utilizations can be assessed to be in the range of 9 – 16 MJ Nm^{-3} that corresponds to methane volume concentrations between 30% and 50%. Table 1 shows the adopted parameters and the characteristics of the gas engine considered for the plant simulations.

3. Modeling

The reacting stages of the plant (gasifier, burner, engine) have been modeled with a thermodynamic chemical equilibrium approach supplemented with an evaluation of the energy fluxes arising from the other components needed for the actual operation. To this purpose, a code written in Matlab environment has been developed using the Cantera software library (a collection of object-oriented software tools for problems involving chemical kinetics, thermodynamics and transport phenomena [7]). The solver implemented in Cantera is a version of the Villars-Cruise-Smith (VCS) algorithm (a well suited method to handle multiphase problems), that finds the composition minimizing the total Gibbs free energy of a mixture [8]. The NASA [9] and the GRI-MECH [10] databases have been used to evaluate the thermodynamic properties of the chemical species considered in the model. The applied procedure for solving the minimization problem is based on the stoichiometric formulation, in which the closed-system constraint is treated by means of the linearly independent stoichiometric equations (1) so as to result in an unconstrained minimization problem

$$\mathbf{n} = \mathbf{n^0} + \sum_{j=1}^{R} \nu_j \xi_j \qquad (1)$$

where n^0 is the initial composition vector, ν_j represents the stoichiometric coefficients vector and ξ_j are the so called ‘reaction coordinates’.

The minimization procedure applied to the G function implies the computation of its partial derivatives with respect to the reaction coordinates (2) and gives the equilibrium condition (3)

$$\left(\frac{\partial G}{\partial \xi_j}\right)_{T,P,\xi_{k\neq j}} = \sum_{i=1}^{N} \left(\frac{\partial G}{\partial n_i}\right)_{T,P,n_{k\neq j}} \left(\frac{\partial n_i}{\partial \xi_j}\right)_{\xi_{k\neq j}} \qquad (2)$$

$$\sum_i \nu_{ij} \mu_i = 0 \qquad (3)$$

where n_i represents the number of moles and μ_i is the chemical potential.

The VCS algorithm utilizes this procedure, and it is very useful when dealing with only a few independent stoichiometric equations. Among the set of states which satisfy the element mass balance, VCS algorithm finds the state with the lowest total Gibbs free energy.

To estimate the yield of both the gaseous and solid phases, an improved two-phase formulation of the model has been used. For the reaction products, 61 chemical species - 60 in the gaseous phase and 1 in the solid state (i.e. the graphite allotropic form of carbon) - are taken into account. The chosen compounds are composed of the C, H, O, N and S elements characterizing the biomass. The calculated yield of solid carbon can be used as an estimate of the actual char and tar residue of the thermal conversion process.

4. Results

In order to assess the syngas quality and to reach high conversion efficiencies, the steam gasification process has been investigated varying both the SC (i.e. steam to carbon) ratio and the conversion temperature. First of all the carbon conversion efficiency (char production as mass fraction) and the syngas molar concentrations of hydrogen, methane and carbon monoxide (as they represent the gaseous species of higher heating value) have been considered. Figure 1 shows that there is complete carbon conversion (no solid carbon production) at every considered gasification temperature for SC greater than 0.8; this threshold decrease to SC = 0.5 for temperature greater than 700°C. Both hydrogen and carbon monoxide concentrations have a decreasing trend with growing SC: in fact the greater the steam supplied to the process, the greater the conversion of H_2 into H_2O and of CO into CO_2. Methane concentration presents the same behavior with SC and, furthermore, the greater the process temperature, the lower its production according to the reforming equilibrium reactions.

The balance of plant has been carried out estimating the mass and energy fluxes needed to generate the desired electrical and thermal power (290 kW_{el}, 350kW_{th}) and to provide the heat and the electricity necessary for the internal consumptions (gasification reactions enthalpy, clean-up energy demand, fume heating). Figure 2 shows the mass balance and points out the temperatures reached by the different streams through the plant, while figure 3 describes the energy flow chart of the plant.

The gasification temperature (750°C) and the SC ratio (0.75) have been chosen by means of an optimization procedure (see par 4.3), while the burner temperature (903°) and equivalence ratio (ER = 1.2) have been computed so that the burner flue gas enthalpy can be exploited to sustain the gasification reactions. For this purpose, it has been adopted a tubular stainless steel reactor (0.25m internal diameter, 5mm wall thickness) surrounded by an external cylindrical steel jacket (0.32m internal diameter), in which flows the hot flue gas from the coupled burner. The model computes the flue gas mass flow ($0.52 m^3 s^{-1}$) and its average speed on the jacket cross-section ($6 ms^{-1}$). Then, once the geometry of the tubes and the biomass bulk density ($192 kg\ m^{-3}$) have been chosen, and also the residence time (of the feedstock in the reactor) has been assumed (1200s), it is possible to calculate the required reactor length (1.7m).

As mentioned above, the biomass energy content ($P_{IN\ (BIOMASS)}$) is exploited both for generating the heat and the steam necessary to the gasification stage ($P_{SYNG\ (RIC)}$) and for fueling the IC engine ($P_{SYNG\ (ENG)}$). Moreover, all the produced syngas is subjected to a recovering process at the gasifier outlet (750-140°C) in order to obtain thermal power (P_{RECOV}) available for external consumers ($P_{NET\ RECOV}$) and for heating the fume before the chimney ($P_{HEATING}$).

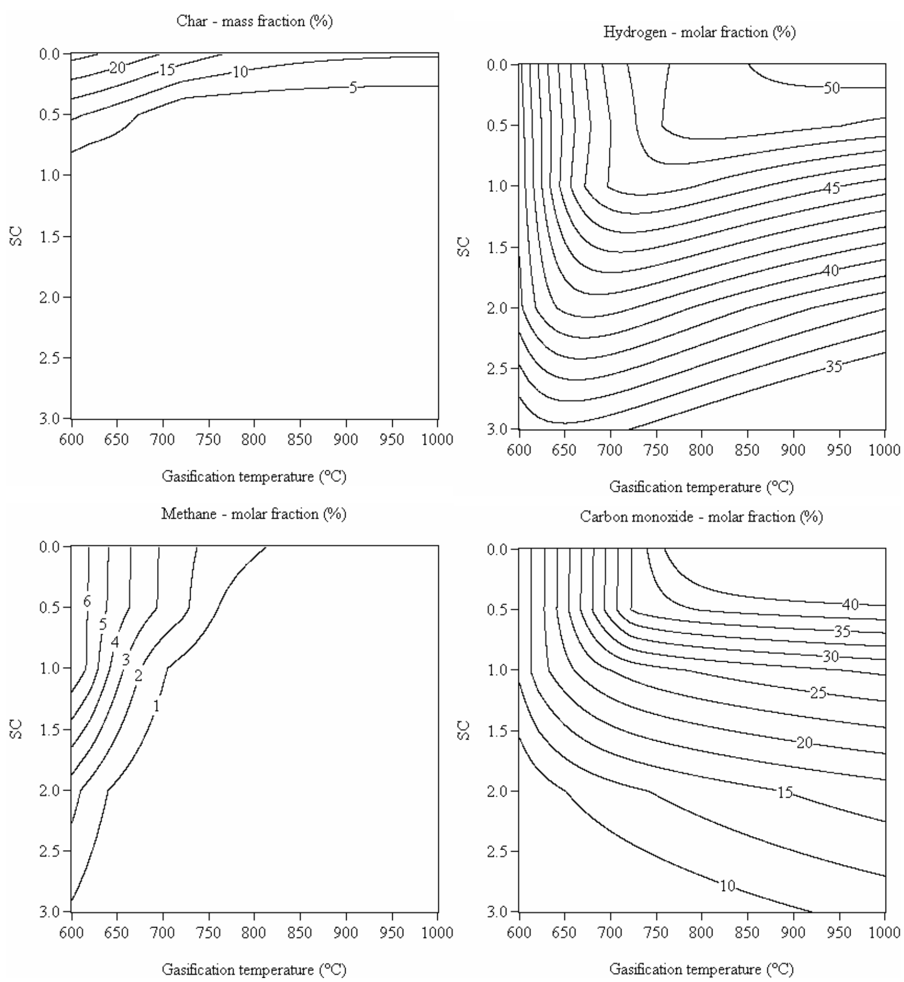

Figure 1. Char and syngas characterization.

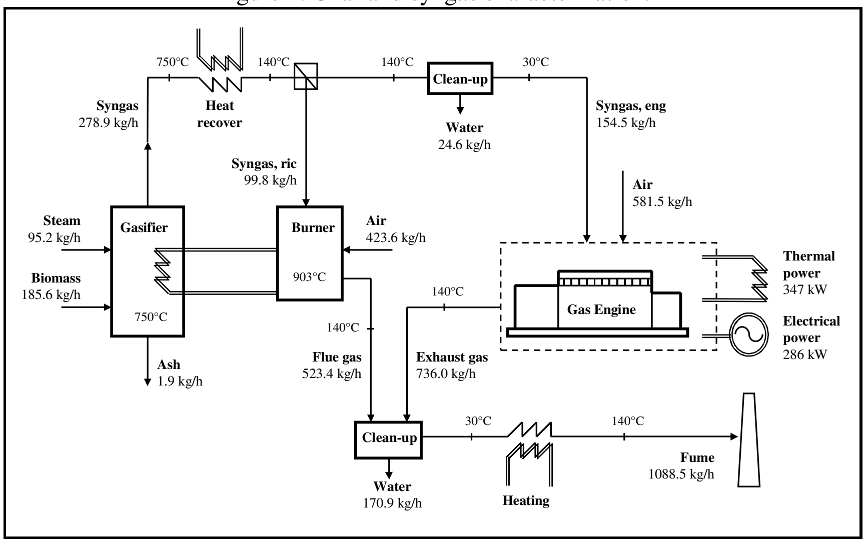

Figure 2. Plant layout and mass fluxes.

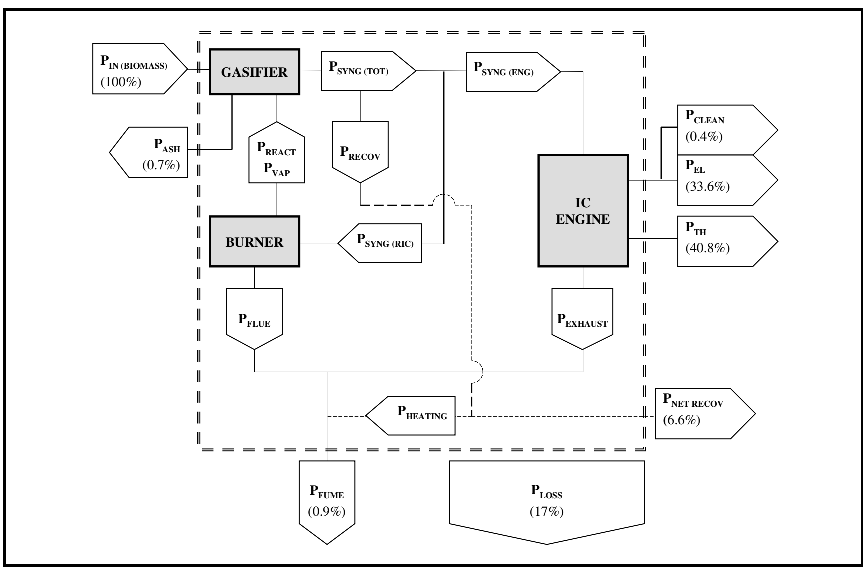

Figure 3. Energy fluxes.

The global plant efficiency, assessed at 81% (4), as been computed as the sum of the total generated power by means of the gas engine (P_{EL} and P_{TH}), plus the net heat recovered from the syngas stream ($P_{NET\ RECOV}$), minus the electric internal consumptions (P_{CLEAN}).

$$\eta_{PLANT} = \frac{P_{EL} + P_{TH} + P_{NET \cdot RECOV} - P_{CLEAN}}{P_{IN}\ (BIOMASS)} \quad (4)$$

The major fraction of the energy loss (P_{LOSS} - 17% of the inlet power) has been estimated to be mainly due to the latent water heat exiting the system from the clean-up stages: in fact, existing scrubbing technologies do not allow for the recovering of this energy fraction, causing a significant loss for the whole system. Furthermore, the latent heat has not been taken into account in the recovery of the available thermal energy from the exhaust gases (considered at 140°C at the plant chimney), since the lower heating value has been considered as inlet power for the feedstock. The other losses are relevant to the ash fraction (P_{ASH} – 0.7%) and the combustion products stream (P_{FUME} – 0.9%) exiting the system.

The best operating conditions have been estimated by means of an optimization procedure. It consists in evaluating the dry syngas lower heating value (LHV - dry basis) and the global plant efficiency, varying the SC ratio and the gasification temperature and choosing the optimum values. In figure 4a it is possible to observe a decrease of the syngas LHV both for increasing SC values (10.5 ÷ 7.5 MJ Nm^{-3}) and with temperature greater than 700°C. In this diagram, SC values between 0.5 and 1 a give syngas LHVs in agreement with the engine requirements (9-10 MJ Nm^{-3}) for all the tested temperatures. On the other hand the global efficiency analysis (figure 4b) gives 1.5 ÷ 2.2 SC as optimum values and narrows the desired temperature range at values greater than 700°C, where the efficiency tends to increase (83% maximum value).

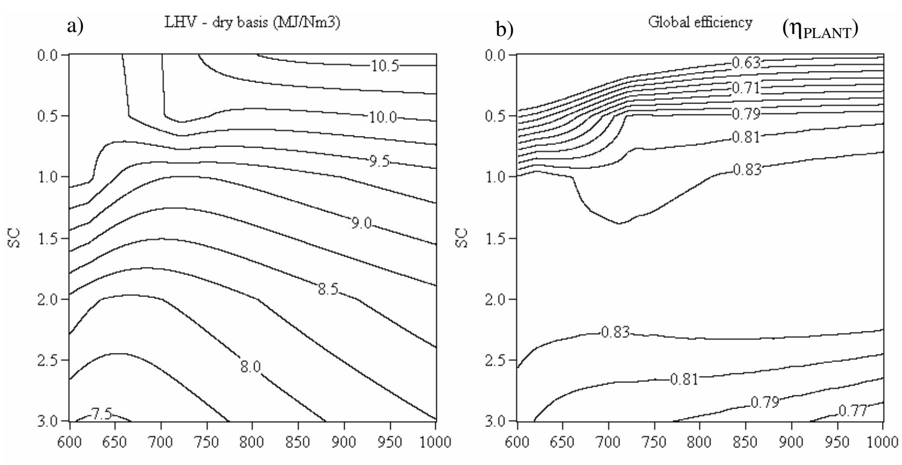

Figure 4. Optimization procedure results

Thus, it is worth to assume a SC ratio of 0.5 and a temperature of 750°C, accepting a design value of the global efficiency (81%), slightly lower than the maximum reachable one, in order to achieve the syngas energy content necessary for the engine (9.4MJ Nm^{-3}). Furthermore, the chosen process parameters allow to obtain an high-quality syngas, characterized by low volume concentrations of the considered pollutants (H_2S = 57.7ppmv, NH_3 = 3.1ppmv on a wet basis).

6. Conclusions

An equilibrium simulation of a small-scale biomass gasification plant has been performed in order to assess the global efficiency and the influence of the process parameters on the performance of the whole system. First of all, a significant electrical efficiency (33.6%) has been estimated, that is even better than those reached by some traditional fossil-fuel plants; in particular, it has been quantified a biomass amount of 1.5 kg of spruce sawdust in order to produce 1 kWh of electric energy. The considered plant configuration allows the recovery of a remarkable thermal energy fraction released at high temperatures on the syngas line and at the burner exhaust outlet, which, if exploited, makes it possible to reach a theoretical global energy efficiency of 81%. Moreover, considering the chosen plant size, it seems reasonable to exploit the produced thermal power at local scale, avoiding the installation of an extended and expensive district heating network. As a conclusion, this solution can be particularly suitable for distributed energy production, especially in small towns situated in rural zones, where there is often available a large quantity of biomass waste (e.g. from wood industry).

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