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Validation of a Small Scale Woody Biomass Downdraft Gasification Plant Coupled with Gas Engine

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In recent years, small scale cogeneration systems (< 500 kW_e) distributed in different geographical locations using biomass has received special attention as economically competitive and environmentally friendly ways of producing energy. These systems can be integrated to industrial and agricultural activities where biomass residues are generated and can be converted into electricity and thermal energy by combustion or gasification. The legislations of many European countries such as Italy concerning renewable energy and energy efficiency along the taxation schemes have raised the incentives for small scale cogeneration plants. Consequently, there is a clear economic interest of the companies in this sector and there is also a scientific interest towards demonstration of their energetic efficiency, environmental performance and reliability.

Among the suggested technologies for the biomass conversion into energy, downdraft gasification (using air as gasification agent), coupled with internal combustion engines, has the advantage of high electric efficiency (~ 25%) and low tar generation, making easier the gas cleaning process necessary for its use into engines.

In the present work, the results of a measurement campaign performed on a commercial scale 350 kW_{th} downdraft woodchips gasification plant, coupled with an SI internal combustion engine (ICE), are presented and discussed. The main goals of this first experimental campaign have been to verify the stability of gasifier and engine operation, operability of the plant and to determine its energy efficiency. The campaign verified a stable operation of the gasifier and the plant produced a syngas with a composition suitable for a gas engine. The energy balance resulted in a potential overall wood fuel to electricity efficiency of about 23 %.

1. Introduction

The decarbonisation of the energy sector is an ongoing process in Europe. A transition from fossil fuels to other forms of energy in special way to renewable energy sources and mainly biomass is observed. Currently, woody biomass is the largest biomass energy resource worldwide. Agricultural waste, forest residues or even organic fraction of the municipal waste are the most significant biomass sources. In Italy new legislations (Italian Ministry of Economic Development. National Law No. 244/2007 Italian Ministry of Economic Development, Italy National Renewable Energy Action Plan, 2010 and Decree of 6/7/2012) about the renewable energy along with the taxation schemes deployed in the last years have raised the incentives for small scale combined heat and power (CHP) applications (< 500 kW_e). Gasification is one of the promising technologies to convert renewable biomass to gaseous fuels for distributed power generation. Forest residues in the form of wood chips, agricultural residues, municipal organic wastes are the most common biomass energy resources worldwide. To invest on biomass gasification rather than on conventional technologies (e.g. combustion boilers coupled with steam engines) shows advantages when it is applied at small scale (< 1 MW_{th}). These advantages can be identified as the use of ICE or microturbines, along with the possibility of combined heat and power production (CHP) (Vakalis et al., 2013; Frigo et al. 2014). Furthermore syngas is a much more flexible product, easily transportable and furthermore it can be used in production of chemicals.

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However, the current state of this technology is still not completely mature for the market and this is reflected in various types and designs of gasification plants. Among the suggested gasification technologies for the biomass conversion into energy, downdraft gasification (using air as gasification agent), coupled with internal combustion engines, has the advantage of high electric efficiency (~ 25%) and low tar generation, making easier the gas cleaning process necessary for use in ignition gas engines. In this work, an experimental campaign has been performed on a commercial scale 350 kW_{th} downdraft woodchips gasification plant coupled with a gas engine. The main goal of this preliminary campaign have been to verify the operability of the plant and stability of gasification in terms of temperature profile and gas composition and to determinate the overall energetic efficiency.

2. Experimental

Gasification tests were performed in a full scale biomass gasification power plant with a nominal capacity of 70 kg/h (10% moisture), designed by the authors of this work and built by Glass Service srl, Italy. Its schematic flowsheet is reported in Figure 1. It consists of a biomass dryer, a downdraft gasifier (type Imbert), gas cooling and cleaning systems, and an internal combustion engine (ICE). The woodchips used were a mix of beech and chestnut from local forest maintenance. The virgin chipped biomass with an average moisture content of 35 wt.% was dried up to about 8 wt.% moisture content using a concurrent rotating dryer fed. The drying medium was a air mixed with the exhaust hot gas from the engine to obtain an inlet gas temperature of about 100 °C. Average properties of the dried wood chips used in the gasifier were determined through standard methods at several times during the whole experimental campaign. The dried chips were fed to the gasifier using an inclined screw conveyor. The gasifier was periodically fed using a time log for the filling starting and a level sensor for the filling stopping. The mass flow of the dryer and the gasifier is in average balanced and a storage bin was adopted to store the biomass from the dryer between two successive fillings.

The gasification reactor is a fixed-bed downdraft gasifier with throat operating at atmospheric pressure where gasification air, preheated at 350-400 °C, was fed from nozzles in the middle part of the gasifier. The gasifier is a stainless steel cylindrical reactor with a height of about 3 m. It is externally covered with an isolation blanket to reduce heat loss and internally coated with ceramic refractory material. The gasifier is equipped with seven type K thermocouples disposed along the bed in order to evaluate the temperature profile. The syngas leaves the gasifier from the bottom. A suitable extraction system in the lower part of the reactor assures the evacuation of the unburnt chars and avoids that the ashes block the gas outlet section.

At the outlet of the gasifier, a high efficiency cyclone was used to remove dust and particles from the gas stream. In order to cool the gas, two shell-and-tube heat exchangers are adopted: in the first heat exchanger the syngas preheats the gasification air while in the second one the gas is cooled by atmospheric air. In the experimental facility this cooling air is dispersed into the atmosphere, but in a commercial configuration this heat could be effectively exploited to satisfy requirements of a thermal end-user. After the cooling, a filter assures the removal of condensate and tar in order to reach the requirements of gas quality for the ICE. To run an ICE with the product gas over a long period of time, the tar and particulate matter contents of the cleaned gas have to be less than 100 and 50 mg/Nm^3 (Asadullah, 2014), respectively.

When the plant was operating in steady state and the flame at the flare was stable, the cleaned gas was fed to a turbocharged SI engine, 6.7 L six cylinders in line (liquid cooled). The engine, coupled with an electric generator, was selected and developed in collaboration with Ecomotive Solutions (AL, Italy) starting from an IVECO Diesel engine (model N67-TM3A, usually adopted in stationary applications) modified into an Otto cycle engine with bore and stroke of 104 and 132 mm, respectively. Main adjustments regarded the replacement of the original Diesel injection system with a spark plug ignition system and the adoption of a special "carburettor" to mix properly the syngas with air. Moreover, the original 17:1 compression ratio was reduced to 8:1 changing the pistons and a phonic wheel was added for crank-shaft position determination. The ignition system is controlled by a dedicated electronic control unit while the ignition advance was adjusted to obtain the maximum brake torque (MBT). The engine was connected to an electric generator (genset) for power generation application. In the experimental facility the electric load of the ICE was a pack of air cooled electric resistances, where the electricity was dissipated.

The circulation of the syngas was assured both by a fan and by the engine. Each gasification test lasted from 6 to 8 hours. In the start-up phase, the required head for the air suction and syngas circulation was provided by the fan and the syngas was burnt in a combustion chamber. When the plant reached the steady operative conditions and the syngas quality was suitable for the engine requirements, the syngas stream was switched from the combustion chamber to the engine and the fan was stopped. In this case, the combustion engine was able to create the right vacuum to suck both the combustion air and the syngas through the plant.

During the start-up, when the syngas temperature was not enough high to preheat the air to the required value, the air was preheated by an electric heater. The presence of the electric pre-heater made possible to reduce the duration of the plant starting time and facilitated the reaching of the steady state conditions. The starting of the gasification reactions can be obtained either using a specific external electric hot air fan or fluxing for several minutes the high temperature air through the biomass bed.

Each section of the plant is instrumented to monitor continuously parameters such as temperature, pressure, volume flow of the gasification air and syngas from the outlet of the gasifier to the combustion chamber or the engine.

Equivalent ratio (ER) values of 0.3-0.35 were used. ER was calculated as follows:

$$ER = \frac{\text{air used for gasification}}{\text{stoichiometric air for complete combustion}} \tag{1}$$

To evaluate the amount of air needed for stoichiometric combustion of the feedstock, carbon and hydrogen contents are considered.

When the gasifier was running stable (i.e. stable temperature profiles in the bed reactor), the producer gas was sampled downstream the cleaning systems every half an hour by gas sampling bags and analyzed in terms of CO, H_2, CO_2, CH_4, H_2, N_2, O_2, C_2H_2, C_2H_4, C_2H_6 contents by a gas-chromatograph coupled with a mass spectrometer (Agilent 5975C series GC/MSD System). At the steady state, gas samples were also collected upstream of the cyclone to measure the contents of dust (method used: UNI EN 13284:2002) and tar using a suitable sampling probe that was designed and constructed in accordance with the tar Protocol (UNI CEN/TS 15439:2008). During gasification run, the solid residues (unburnt char and ash) were extracted at the bottom of the gasifier by a screw conveyor. At the end they were weighted and analyzed in terms of carbon and ash content.

The gasifier performance was evaluated in terms of the specific dry gas yield (η_{gas}), lower heating value (LHV) of the dry product gas, cold gas efficiency (CGE) and percentage of carbon in the feedstock recovered in the gas (y_{carbon}). The dry product gas LHV was calculated from the average composition of the dry product gas using the following equation:

$$LHV\ (kJ/Nm^3) = y_{CO} \times 12621 + y_{H_2} \times 10779 + y_{CH_4} \times 35874 + y_{C_2H_2} \times 56020 + y_{C_2H_4} \times 59483 + y_{C_2H_6} \times 64423 \tag{2}$$

where y_i values are mole fractions of main combustible components in the dry producer gas.

CGE was evaluated as follows:

$$CGE(\%) = \frac{\text{dry product gas flowrate} \times LHV_{\text{dry gas}}}{\text{dry biomass flowrate} \times LHV_{\text{dry biomass}}} \times 100 \tag{3}$$

and η_{gas} was calculated per weight of dry feedstock as follows:

$$\eta_{gas} = \frac{\text{dry product gas } (Nm^3)}{\text{dry feedstock } (kg)} \tag{4}$$

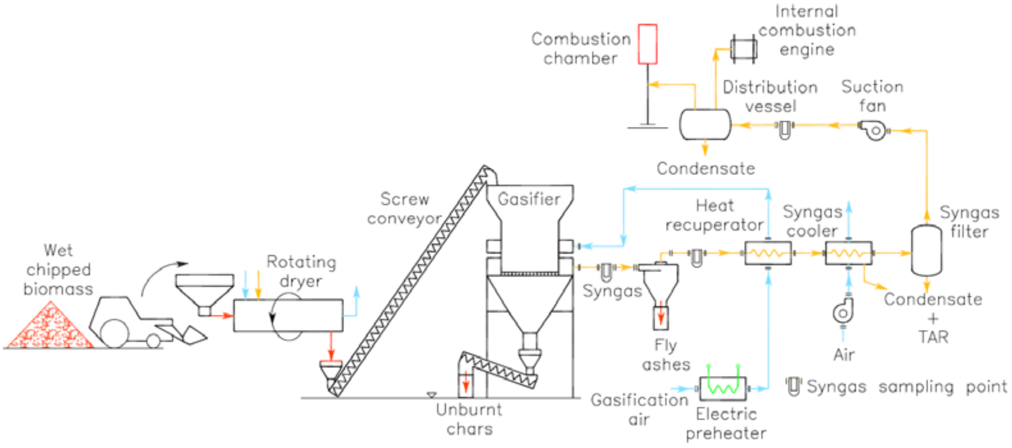

Figure 1: Schematic flowsheet of the full scale downdraft gasification plant

3. Results and discussion

The average properties of the dried wood chips fed to the gasifier are reported in Table 2. Regarding the process stability, the gasification was a highly reproducible process with regular steady states even if, sometimes, the solid discharge caused significant heat loss and changes in the temperature profiles along the bed with the introduction of instabilities in the gasification process in terms of gas production and quality. No agglomeration problems were seen.

A typical average axial temperature profile measured at the steady-state along the gasifier bed at ER of 0.3 is reported in Figure 2. The temperature profile is representative of the different processes stratified occurring along the reactor axis from top to bottom: drying, pyrolysis, combustion and gasification. Drying starts where the feedstock enters the gasifier, in this zone the residual moisture of the biomass vaporizes. Above temperatures of around 200 °C pyrolysis occurs and the biomass starts to thermally decompose to products such as char, tar and volatiles by means of heat at low oxygen amount. When the biomass reaches the combustion zone at the throat, where sub-stoichiometric air is supplied, the pyrolysis products are partially combusted and the peak temperatures are reached. The combustion processes provide the necessary heat for the pyrolysis, drying and gasification (reduction). Finally, below the combustion zone at about 700-800 °C the gasification reactions occur and the syngas is produced. When the gas leaves the reactor, its temperature is about 600-700 °C. At outlet of the cyclone, the gas temperatures were 400-450 °C.

Table 1: Properties of the dried wood chips

Average size (mm x mm x mm)	20 x 8 x 4		
Bulk density (kg/m^3)	274		
Proximate analysis		**Ultimate analysis**	
Moisture (wt %)	8.2	Carbon (wt %, dry ash free)	49.23
Volatile matter (wt %, dry)	80.27	Hydrogen (wt %, dry ash free)	5.60
Ash (wt %, dry)	0.22	Nitrogen (wt %, dry ash free)	0.19
Fixed carbon (by diff. wt %, dry)	19.51	Oxygen (by diff. wt %, dry ash free)	44.98
Calorific values			
HHV (MJ/kg$_{dry}$)	18.98		
LHV (MJ/kg$_{dry}$)	17.83		

Table 2 reports the operating conditions for the gasification experiments performed and the corresponding results. The major combustible gaseous products have been CO, H_2, CH_4 and C_2H_4 and it is worth noticing that the gas compositions and the dry gas heating values were close to those measured in industrial downdraft gasifiers (Reed and Das, 1988; Kumar et al., 2009, Biagini et al., 2014). In the range ER = 0.3-0.35, the average concentrations of dust and tar measured in the gas before the cyclone were about 215 mg/Nm^3 and 1,700 mg/Nm^3, respectively. Also these values fall within the range reported in the literature for dust, 100-8,000 mg/Nm^3, and tar contents, 10-6,000 mg/Nm^3 (Asadullah, 2014). Consequently, the results obtained have validated the full scale downdraft gasifier and the gas analysis system used.

First engine tests, mainly concentrated to set the engine parameters, confirmed the suitability of the choice. Engine brake thermal efficiency (EBTE), adopting an air/syngas ratio (by vol.) equal to 1.25, was verified at several electric power levels. As aforesaid, during this preliminary engine activity, the alternator was not connected to the public electric grid but an adjustable resistive load was applied. Figure 3 shows these first results considering an average syngas LHV of 5.5 MJ/Nm^3 and taking into consideration an efficiency of 0.9 for the electric generator. Therefore, considering an average biomass to gas efficiency of 73 % and a gas to electricity efficiency of 35 % an overall gross efficiency (from wood fuel to electricity delivered to the grid) of about 25 % was obtained considering negligible the electricity consumptions of the plant.

When the electric load of the engine decreased, it happened evidently that the syngas flow, that was sucked, decreased, too. Hence, the thermal load of the gasifier became lower and, consequently, the peak of the profile temperature within the reactor dropped markedly. This fact affected the syngas quality, in terms of TAR content and lower heating value. From the experimental activity the lowest percentage allowable electric load resulted equal to about 25-30% that can be considered a very low value.

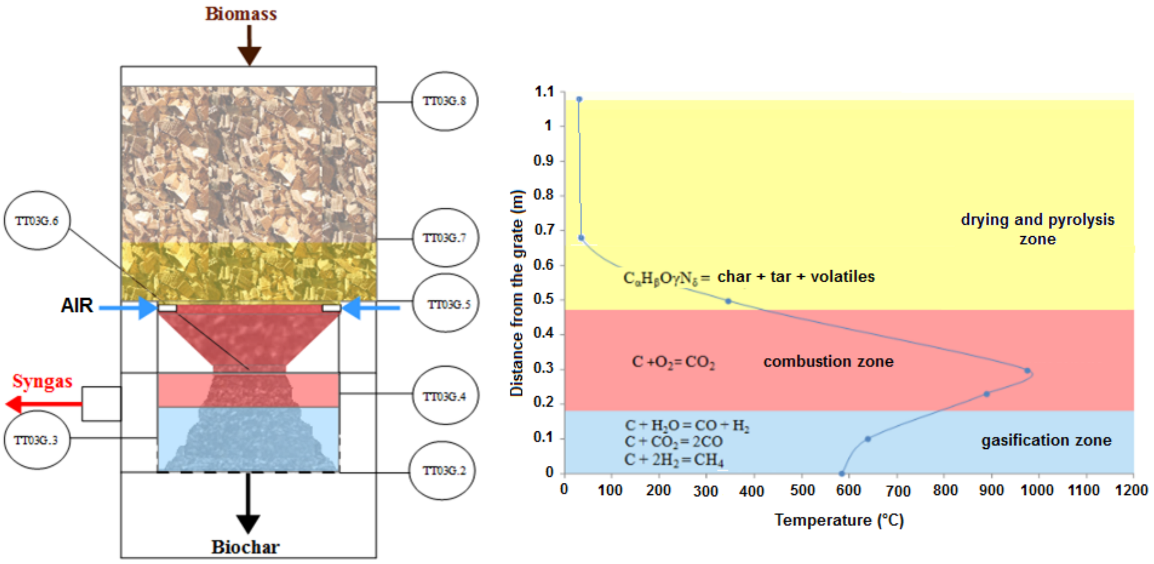

Figure 2: Average temperature profile at the stationary state along the gasifier at ER = 0.3

Table 2: Experimental results of gasification tests

Dried feed rate (kg/h)	67.3	43.6	47.5	65.8	Literature values *
ER	0.30	0.30	0.32	0.35	0.25-0.3
Dry product gas /Feed (Nm^3/kg_{dry})	2.04	2.29	2.22	2.42	2-2.4
Dry gas composition (vol.%)					
H_2	11.2	16.1	12.9	15.1	12 - 20
CO	24.7	24.8	24.8	23.7	17 - 22
CH_4	2.73	1.82	2.66	1.67	2 - 3
C_2H_2	0.171	0.039	0.149	0.185	< 1
C_2H_4	0.766	0.382	0.721	0.353	< 1
C_2H_6	0.115	0.053	0.099	0.038	< 1
Combustible gas	39.682	43.194	41.329	41.046	
CO_2	11.2	10.9	10.8	9.6	10 - 15
N_2 (+ O_2 traces)	49.1	45.9	47.9	49.4	50 - 54
LHV (MJ/Nm^3)	5.94	5.74	6.05	5.56	5 - 6
y_{carbon}	92.9	95.5	96.9	95.0	-
CGE (%)	67.5	73.7	75.1	75.4	60 - 75

* Ref. (Reed and Das, 1988; Kumar et al., 2009, Biagini et al., 2014)

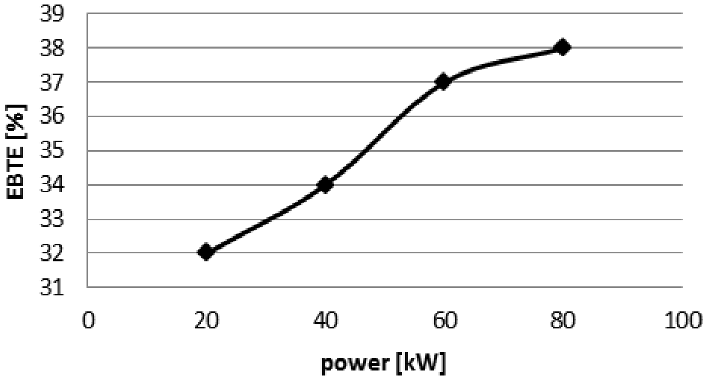

Figure 3: EBTE at several electric power levels, 1500 rpm and air/syngas ratio (by vol.) = 1.25.

4. Conclusions

A complete experimental full-scale biomass gasification CHP plant with downdraft gasifier has been designed and installed. During a measurement campaign, the operation of the plant, that with a nominal thermal power of about 350 kW_{th} produced a syngas with a composition suitable for internal combustion engine operation, was validated. At the steady state, the syngas composition was similar to those reported in literature for industrial downdraft gasifiers. The TAR content of the syngas fell within the literature range, too. The operative behaviour of the plant was stable within a wide range of thermal load.

The energy balance for the plant operating with ER values of 0.3-0.35 shows an average biomass to gas efficiency of 73%, a gas to electricity efficiency of roughly 35 % and an overall wood to electricity efficiency of about 25 %.

First engine tests put in evidence the suitability of the strategies implemented, in particular the modifications operated on the engine and the air-syngas mixing device adopted, with a final engine brake thermal efficiency of 38% at maximum load.

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