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Gasification of agricultural residues in a demonstrative plant: Corn cobs

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HIGHLIGHTS

- Experimental gasification tests are carried out with a biomass waste (corn cobs).
- The gasifier is a downdraft reactor at a demonstrative scale (350 kWth).
- Material and energy balances revealed interesting gas production and power efficiency.
- Fluctuations in gas composition and pressure drop are imputed to the reactor dynamic.

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ABSTRACT

Biomass gasification couples the high power efficiency with the possibility of valuably using the byproducts heat and biochar. The use of agricultural wastes instead of woody feedstock extends the seasonal availability of biomasses. The downdraft type is the most used reactor but has narrow ranges of feedstock specifications (above all on moisture and particle size distribution), so tests on a demonstrative scale are conducted to prove the versatility of the gasifier. Measurements on pressure drops, syngas flow rate and composition are studied to assess the feasibility of such operations with corn cobs. Material and energy balances, and performance indexes are compared for the four tests carried out under different biomass loads (66–85 kg/h). A good operability of the plant and interesting results are obtained (gas specific production of 2 m^3/kg, gas heating value 5.6–5.8 MJ/m^3, cold gas efficiency in the range 66–68%, potential net power efficiency 21.1–21.6%).

1. Introduction

Gasification with air in a downdraft reactor coupled to an internal combustion engine is one of the most promising biomass-to-energy applications on a small scale, because of the higher power efficiency with respect to any direct combustion based system. Further advantages of this solution are the relatively higher quality of syngas produced compared to other gasifiers (Hasler and Nussbaumer, 1999), with potential conversion to valuable chemicals, like methanol and hydrogen, the possibility of utilizing the by-products (biochar as a soil amendment, recovery heat for cogeneration), the low emissions due to the combustion of a gas instead of a solid. The open issues concern the limitations on feedstock specifications (low moisture, narrow dimensional range, as discussed in Simone et al., 2009; Martinez et al., 2012), the high level required in the syngas cleaning (especially for tar and dust), and the disposal of waste water and/or filter media used for the clean-up.

Most studies on downdraft gasifiers used woody materials (chips, briquettes, pellets) as feedstock (see for instance Zainal et al., 2002; Sharma, 2011; Simone et al., 2012). It is important to prove the operability of the gasifier with feedstocks other than the reference ones in order to extend the diffusion of this technology and make it more attractive to farmers. This would overcome the supply limitations related to the seasonal availability of biomasses. Agricultural by-products and food residues are among the most interesting, and sometimes cheapest, candidates for (entirely or partially) substituting the woody feedstock in a downdraft gasifier. Due the wide variety in origin, composition, particle size distribution, many of them represent out-of-specification fuels and are not suitable for the direct gasification. Low temperatures (due to high moisture content, for instance), scarce flowability or obstructions (due to the presence of fines or long particles) inside the reactor, can compromise the operations of fixed bed reactors (see for instance Wander et al., 2004). Pretreatments (drying, chipping, sieving, densification, see Erlich and Fransson, 2011), mixing

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out-of-specification with reference feedstocks, or specific technical operations (e.g. use of vibrators for favoring the flowability), may extend the use of biomass residues in such reactors.

This work is included in the regional research project "Bio-Power in Tuscany" funded by Regione Toscana (Italy), aiming at proving the feasibility of a distributed energy generation in small plants that use biomass sources on a regional area. It is also part of the programmed activities on agricultural and forest biomasses (see preliminary results in Biagini et al., 2014) to be tested in the gasification plant at CRIBE (Biomass-to-Energy Interuniversity Research Center). The gasification tests with an agricultural residue (corn cobs) in a demonstrative scale downdraft gasifier (nominal thermal throughput of 350 kW) are described in the following sections. The study aims at assessing the feasibility and reliability of the gasification operation with an out-of-specification feedstock, and providing a process evaluation of the plant performance.

Typical corn cob yield is around 1 t (dry)/ha (Schmer and Dose, 2014). The huge worldwide production of corn (870 Mt/y in 2011, see Zhang et al., 2012), corn cobs representing 18% of the total amount, has stimulated different energetic applications of its residues, such as thermochemical (for producing bio-oil and chemicals, biochar and activated carbons, see Tsai et al., 2001; Cao et al., 2006; Ioannidou et al., 2009; Mullen et al., 2010; Branca et al., 2012; Demiral et al., 2012) and biological (for producing bioethanol, Latif and Rajoka, 2001; Chen et al., 2010) treatments. Few works on gasification of corn cobs can be found (Jin et al., 2010; Zhao et al., 2011), none of them on a demonstrative scale. So this work contains interesting data for assessing the feasibility of corn cobs gasification for power production on a small scale, suitable for farmers to recover energy in a local context.

2. Methods

2.1. Fuel characterization

The activities of the plant are supported by the laboratory at DICI (Department of Industrial and Civil Engineering of the University of Pisa-Italy), where the characterization of the solid fuels is carried out. The moisture content and bulk density of the corn cobs samples are evaluated according to the European standard test methods EN 14774-1 and EN 15103, respectively. Volatile Matter (VM), Fixed Carbon (FC) and Ash content are determined by thermogravimetric (TG) analysis. A TA Q-500 thermobalance is employed for TG analysis. Ultimate analysis is carried out with a LECO TruSpec CHN Elemental Analyzer, according to EN 15104 test method. A LECO AC-500 Isoperibol Calorimeter is used for determining the Heating Value (HV), according to EN 14918 test method. The particle size distribution is obtained according to EN 15149-1. The results for the corn cobs samples are listed in Table 1. As can be seen from the particle size distribution, there is no large particle (i.e. with a dimension greater than 63 mm), while the amount of fine particles (<8 mm) is significant. The bulk density is 240 kg/m^3 for the material as received. The Higher and Lower Heating Values on a dry basis are 18.56 and 17.33 MJ/kg, respectively.

2.2. Description of the gasification facility

The Gastone gasification plant (see the flowsheet in Fig. 1) is sited at CRIBE center (Pisa-Italy) and has a maximum thermal input of 350 kW, corresponding to 80 kg/h of biomass with a moisture content of 15%. It can be divided in four sections: feeding apparatus, gasifier and control system, gas clean-up, and water handling. The whole plant occupies an area of 60 m^2. The reactor is a downdraft type, with the biomass fed to the top via a screw conveyor. The plant is operated slightly below atmospheric conditions by a fan-blower positioned at the end of the gas clean-up line. Consequently, air enters the reactor through four nozzles positioned in the throat section. Inside the reactor, the solid drying and devolatilization zones are located above the air injection, while the reduction zone is below the throat/oxidation section. The resulting char bed is supported on a grate at the bottom of the gasifier. The syngas moves from the reactor to the clean-up line, consisting of a cyclone, two packed columns with recirculating vegetable oil, a chiller-condenser, two sawdust filters and a bag filter, which are designed to remove particulates, tar and water from the syngas and make it suitable for the combustion in an engine. Due to the experimental nature of this investigation and the relatively short test time (3–4 h each), the syngas is actually burnt in a flare. More technical details are given in Simone et al. (2012), although some modifications respect to that solution were made before the test campaign with corn cobs. In particular, the original water scrubber was substituted with the two columns with vegetable oil to improve the tar removal. Furthermore, a bigger blower was used (from 2 to 4 kW), allowing to increase the syngas production and, consequently, the biomass feeding rate (from 40 to 80 kg/h).

Several thermocouples are used to measure the syngas temperature in the reactor and along the cleanup line. Previous modeling studies allowed to study the temperature profile inside the reactor (Simone et al., 2013a). Differential manometers give the pressure drops across the gasifier bed and clean-up units to monitor the plant operability. A flow-meter at the end of the clean-up line measures the syngas production. Volumetric data for the gas are expressed in normal conditions, i.e. 0 °C and 1 atm. The amount of material inside the reactor is maintained constant by means of a level control at the top of the gasifier. In stationary conditions, this solution assures a self-regulating air-to-biomass ratio (Reed and Das, 1988). The charcoal discharge is regulated by adjusting the frequency of the rotating grid, to maintain the pressure drop across the charcoal bed in a suitable range.

The plant is equipped with a Gas Chromatograph (micro-GC Agilent 3000) and a Fourier Transformed Infra-Red Spectrometer (Bruker Tensor 37 FTIR spectrometer), positioned at the blower outlet, for online gas analysis. More details are given in Simone et al. (2012, 2013b). Solid samples can be collected from the gasifier bed as well as particles from the cyclone discharge tank. However a quantitative collection of the outlet solid residues is not possible, because the charcoal is washed away from the bottom plate under the grid by a water stream to the water treatment system.

Table 1
Proximate, ultimate and size analyses of corn cobs.

Proximate analysis (%wt)		Ultimate analysis (%wt)		Particle size distribution (%wt)	
Moisture (a.r.)	10.1	C (d.a.f.)	47.60	>63 mm	0.0
VM (dry)	80.06	H (d.a.f.)	6.10	8–63 mm	75.1
FC (dry)	17.82	N (d.a.f.)	0.52	3.15–8 mm	13.4
Ash (dry)	2.12	O (d.a.f.)	45.78	<3.15 mm	11.5

Notes: a.r. as received basis, d.a.f. dry ash free basis.