CHEMICAL ENGINEERING TRANSACTIONS
VOL. 37, 2014
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Eliseo Ranzi, Katharina Kohse- Höinghaus

ISBN 978-88-95608-28-0; **ISSN** 2283-9216
DOI: 10.3303/CET1437026

Gasification of Agricultural Residues in a Demonstrative Plant

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Small size (<1 MW) thermochemical plants producing electricity and heat are a convenient option for biomass-to-energy scenarios. It is required to improve these systems in terms of efficiency and flexibility, extending the feedstock specification and plant reliability. In this work the experimental results of the recent campaigns in the CRIBE gasification plant with out-of-specification feedstocks (pellets, vine prunings, rice husks, corn cobs, miscanthus) are described and discussed. The biomass properties are investigated and related to the technological operations and plant performance for defining the suitable ranges of their characteristics. The morphological parameters (size/shape), density, thermal and mechanical consistency of the material are crucial for the safe operation in the downdraft gasifier. The pretreaments (drying, size reduction, pelletization, mixing of different feedstocks) are necessary for operability and should be optimized considering the overall plant efficiency and costs. This will be evaluated with a process study.

1. Introduction

There is a renewed interest in the biomasses for energy production, with economic, social and environmental benefits (Peres et al. 2013). Intrinsic distributed geographical areas of biomass production suggest to conveniently consider small size (<1 MW) thermochemical reactors producing electricity and heat. This matter falls within the aim of the BPT (BioPower in Tuscany) project funded by the Tuscany Region. It is required to improve these systems in terms of efficiency and flexibility, extending the feedstock specification and plant reliability, thus solving technological specific issues, concerning the solid handling, char conversion and reuse, gas cleanup and tar removal. Biomass gasification with air in downdraft gasifiers coupled to an internal combustion engine is one of the most common small scale applications due to the low tar content of the syngas and high fuel conversion. However, feedstock specifications, such as low moisture and narrow size distribution, limit the reliability and diffusion of this technology. In this work the experimental procedures and significant results of the recent campaigns in the gasification plant located at CRIBE (Interuniversity Research Centre on Biomass for Energy) are described and discussed. The plant is used to demonstrate the technological reliability of this reactor with different feedstocks on a pilot scale plant. The effect of the biomass properties on the syngas quality and technological operations is studied to define the suitable ranges for the fuel characteristics. It is indeed a smart move to extend the acceptable ranges to a variety of fuels:

- to evaluate the possibility for farmers to recover energy from agricultural residues;
- to overcome the supply limitations related to the seasonal availability of biomasses;
- to optimize the preliminary conditionings of the feedstocks (e.g., forced drying, pelletization of fine particles, size reduction, mixing biomasses with different characteristics).

Please cite this article as: Biagini E., Barontini F., Tognotti L., 2014, Gasification of agricultural residues in a demonstrative plant, Chemical Engineering Transactions, 37, 151-156 DOI: 10.3303/CET1437026

2. Experimental section

2.1 Description of the gasification facility

The gasification plant named Gastone (see the flowsheet in Figure 1) has a nominal thermal input of 200 kW, corresponding to 40-50 kg/h of biomass with a moisture content of 15%. It can be grouped in four sections: feeding apparatus, gasifier and control system, gas clean-up, and water handling.

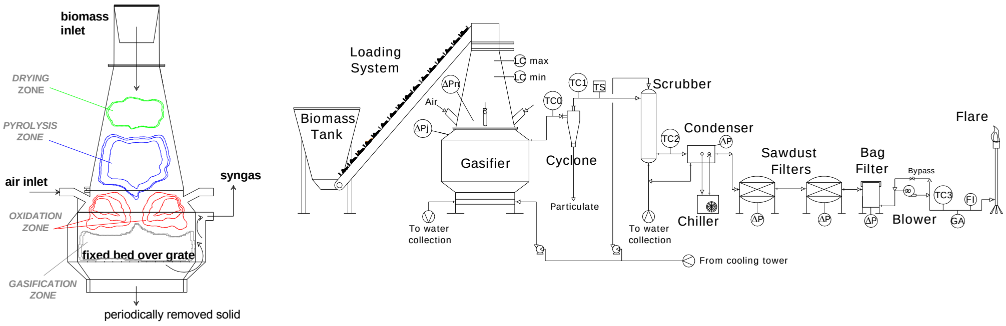

Figure 1: Functional scheme of the gasifier (left) and flow-sheet of the CRIBE gasification facility (right)

The biomass is fed to the top of the gasifier via a screw conveyor. The plant is operated slightly below atmospheric conditions due to 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 (see a scheme of the gasifier in Figure 1). The drying and devolatilization zones are located above the air injection, while the reduction zone below the throat/oxidation section. The biomass is supported on a grate at the bottom of the gasifier. The syngas produced moves to the clean-up line, consisting of a cyclone, a scrubber, a chiller-condenser, two sawdust filters and a bag filter, which are designed to remove tar, particulates and water from the syngas and make it suitable for combustion in an engine. Different thermocouples measure the syngas temperature in the reactor and along the cleanup line. Differential manometers and a flow-meter give the pressure drops across the gasifier bed, monitor the plant operability and measure the syngas production. The plant is equipped with a micro gas chromatograph (GC) and a Fourier Transformed Infra-Red Spectrometer (FTIR), positioned at the blower outlet, for online gas analysis. Condensate can be sampled with an in house developed device. It is also possible to collect solid samples from the gasifier bed as well as particles from the cyclone discharge tank. The activities on the plant are supported by a laboratory where it is possible to carry out conventional characterization of solid fuels.

2.2 Gasifier feedstock specifications

The reference feedstock for the downdraft gasifier is woodchips (Simone et al. 2011). Some other fuels can be actually used if they comply with the fuel specifications reported in Table 1. Many lignocellulosic biomasses (of different origin) can meet such specifications. The crucial specifications concern the moisture content and particle size distribution, which may require a conditioning step of the biomass. The size distribution is indeed a remarkable limitation for agricultural and food residues, since many of them have a small size or even a dusty consistency. Also the shape of many biomass fuels is crucial for operational conditions in the gasifier, although defined specifications are not given on that point.

2.3 Monitoring of the operational parameters

Differential manometers are available in the plant to monitor the following parameters:

- ΔP_j, which is the pressure difference between the atmospheric pressure (P_0) and the pressure in the annular jacket of the gasifier (P_j),
- ΔP_n, the pressure difference between the atmospheric pressure (P_0) and the pressure at the nozzle outlet inside the gasifier (P_n),
- ΔP_g, the pressure drop across the gasifier bed, calculated as the difference between ΔP_j and ΔP_n.

The parameter used to monitor the gasifier operability is X defined as the ratio between the readings of the differential manometers ΔP_n and ΔP_j. It represents the permeability of the bed. For high values of X (that is in case ΔP_n approaches ΔP_j) the pressure drop through the bed is low. This may happen because of a bed by-pass through preferential channels, reduction of the bed depth, switching to combustion regime. This condition should be avoided since it may lead to a low-quality syngas (low heating value), blockage of the biomass loading system, and low biomass conversion. When low values of X are reached, a thickening of

Table 1: Specification of the biomass feedstock

Parameter	Units	Limits	Particle size	Limits
moisture	%wt as received	<20		%wt as received
heating value	MJ/kg dry	>17.5	>100 mm	0
volatile matter at 600°C	%wt dry	>78	63-100 mm	<2
ash content at 900°C	%wt dry	<3	3.15-8 mm	<10
N content	%wt dry	<1	<3.15 mm	<2

the bed or a loss of permeability is occurring, with difficult air flow. Also these conditions should be avoided since they may lead to low syngas flowrate, high tar content, reactor obstruction. The optimal range for X in the Gastone reactor is 0.05-0.20. The X ratio can be controlled by regulating the discharge frequency from the bottom grid. The automatic cycle also controls the biomass loading, by measuring the level in the top section of the gasifier. Finally, the regulation of the by-pass valve on the blower allows the syngas flow-rate to be modulated by increasing the air fed to the reactor.

3. Results of the experimental campaigns

All biomasses tested in this work are out of specifications. In some cases traditional pretreatments (drying, sieving, size reduction) are sufficient for remaining under the limits (see Figure 2 for a qualitative comparison of biomass parameters out and within the envelop of the specifications, before and after the pretreatment). In other cases, more drastic treatments (pelletization, torrefaction, washing) or mixing different feedstocks are necessary to assure safe operations in the gasifier. It is worth noting that the limits of the parameters depend strongly on the reactor configuration. The optimal treatment should be programmed by the preliminary characterization of the feedstock. A further constraint concerns the feasibility of these pretreatments, from different points depending on the energetic convenience, environmental sustainability (for instance loss of material during size reduction) and costs.

3.1 Gasification of pelletized biomasses

Pelletization is a suitable option for biomass conditioning, because it allows the production of stable dry fuels with uniform size from different biomass sources. Remarkably, pelletized biomass fuels have higher density and energy content compared to parent biomasses.

Two pelletized materials were studied: wood sawdust pellet (WSP) and pelletized meal produced from sunflower seeds pressing (SMP). WSP complied with the specifications reported in Table 1. SMP exhibited a high energy content, which made it an attractive fuel, but the ash and nitrogen contents were too high. Consequently, a mixture (MIX) of 50%WSP-50%SMP on a weight basis was created to allow the use of SMP in the downdraft gasifier. The size distribution of WSP and SMP was very homogeneous: they have a cylindrical shape, with a diameter of 6 mm and 10 mm, length 10-30 and 30-60 mm, respectively. Two tests were performed with WSP and two with MIX. Generally, the tests lasted from three to six hours, with the aim to reach and keep constant the maximum syngas flow-rate. Both the pelletized biomasses had good handling properties and this assured a stable feeding of the gasifier.

The pressure drop across the gasifier bed were monitored for all tests. A typical trend of the gas flowrate versus the pressure drop is shown in Figure 3 for test 1 with WSP. In the early stage of Test 1 the syngas flow-rate was almost constant at 90 Nm^3/h, then it was increased up to 130 Nm^3/h by gradually closing the by-pass valve. After about three hours from the ignition, the gasifier pressure drop suddenly changed from 2040 to 3240 Pa with the same syngas flow-rate. This indicates a change in the gasifier permeability.

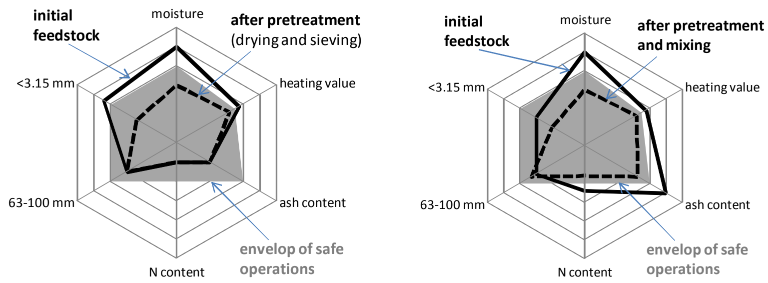

Figure 2: two cases of out-of-specification feedstocks (continuous line) and program of pretreatments (dotted line) to fall within the envelop of safe operation (grey area) in the Gastone gasifier.

Similar results were obtained in the other tests, showing an increasing of the pressure drop with constant (and sometimes decreasing, as for test 4 with MIX, see Figure 3) gas flowrate. So in general, tests with biomass pellets were characterized by low gas flow-rates, high pressure drop and low X ratio. The situation was worse with MIX. In this case the pressure drop was higher (>3000 Pa) indicating a reduction in bed permeability, imputed to the loss of consistency of the pelletized material.

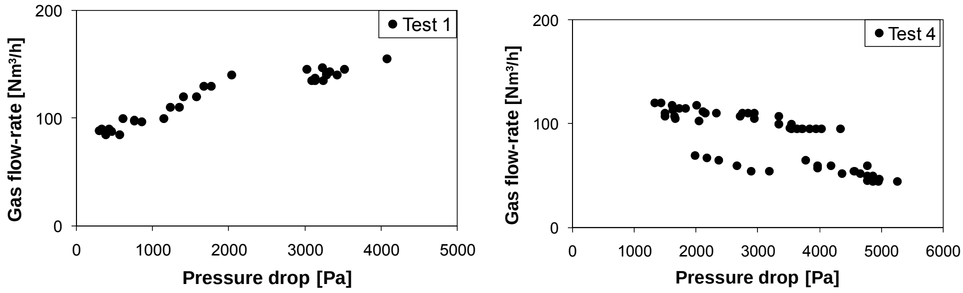

Figure 3: Syngas flowrate versus pressure drop during the gasification of WSP (left) and MIX (right)

As for the operating and performance parameters, the tests were carried out with a biomass load of 45-55 kg/h, an equivalent ratio of around 0.30, a low heating value (LHV) of the produced syngas between 5.5 and 6.0 MJ/Nm^3, a specific gas production (that is volume of syngas per amount of wet biomass) of 2.2 and 2.4 Nm^3/kg for WSP and MIX, respectively, a cold gas efficiency (ratio of the energy output associated to the cold syngas to the energy input associated to the biomass) of 68 and 70%, respectively. Further details can be found in Simone et al. (2012a). These values are in accordance with literature works (see for instance, Erlich and Fransson 2011, Martinez et al. 2012).

3.2 Gasification of agricultural residues

Three agricultural residues, available in Italy, were tested in the Gastone plant: vine prunings, rice husks and corn cobs. Vine prunings complied with the specification of the gasifier except for the dust content (the fraction <3.35 mm was around 12%wt). Thus it was necessary to sieve the material before the tests. Three tests were carried out. A frequent problem was the formation of bridges inside the reactor, which halted the biomass outflow, thus stopping the feed. The problem was partially solved by increasing the vibration provided by an external electric vibrator. The syngas flow-rate achieved during one of the tests with vine prunings is plotted against the X ratio in Figure 4. Each curve was obtained for a different opening level of the by-pass valve, consequently the syngas flow-rate increased from 60 to 150 Nm^3/h in stable conditions. This indicated the formation of a suitable gasification bed in the gasifier. Shutting the by-pass valve led to a general switch of the X ratio towards higher values, but still within the optimal range (<15%). As in the previous tests, the gasification was performed with equivalent ratios around 0.3, gave a syngas with an average LHV of 5.75 MJ/Nm^3, a specific gas production of 2.3-2.5 Nm^3/kg and a cold gas efficiency between 75 and 78%. Further details can be found in Simone et al. (2012b).

The second residue tested was rice husks. It was a material out of specifications, as it showed an ash content of 16.6%wt (dry), and more than 96%wt of fraction size under 3.35 mm. Although not mentioned in the former specifications, also the apparent density is crucial, as a low value (<250 kg/m^3) may compromise the functionality of the plant. In this case it resulted 136 kg/m^3. Also the heating value was quite low, with a LHV of 15.6 MJ/kg. As a consequence of the bad properties of this biomass, the 3 gasification tests were carried out with a low pressure drop across the bed (200-400 Pa), a low value of the syngas heating value (3-4 MJ/Nm^3) and numerous drainages of the reactor, due to the low density of the material, coupled with some combustion of the bed, due to its high permeability. No technical adjustment (like the regulation of the bottom screw and bypass valve) helped in solving these problems.

The last residue tested in Gastone was corn cobs. It was a material with 2.1%wt of ash and a medium heating value (17.5 MJ/kg dry). It resulted without large particles, but a significant fraction of small particles (8%wt in the range 1.18-3.35 mm, 2% in the range <1.18 mm). The apparent density was almost the minimum value required (240 kg/m^3). As a matter of fact the operation of the 3 tests carried out had limited problems, and continuous operations were achieved in the last two tests. The syngas flowrate versus the pressure drop across the gasification bed is shown in Figure 4. The pressure drop resulted rather high but the permeability factor (X ratio) was in the good range (it varied between 6 and 8%). The material and energy balances of the tests with corn cobs gave an equivalent ratio around 0.28, specific productivity 1.9 Nm^3/kg, cold gas efficiency around 60%.

3.3 Gasification of herbaceous biomasses

Although CRIBE is interested in testing three herbaceous available in the Tuscan territory (namely, Arundo Donax, Miscanthus and Panicum Virgatum), so far the gasification tests were carried out only with Mischantus. It was harvested and stored in bales and reached a moisture content of 15%. However the morphological structure was prohibitive, with presence of numerous large and long particles: 41%wt of par-

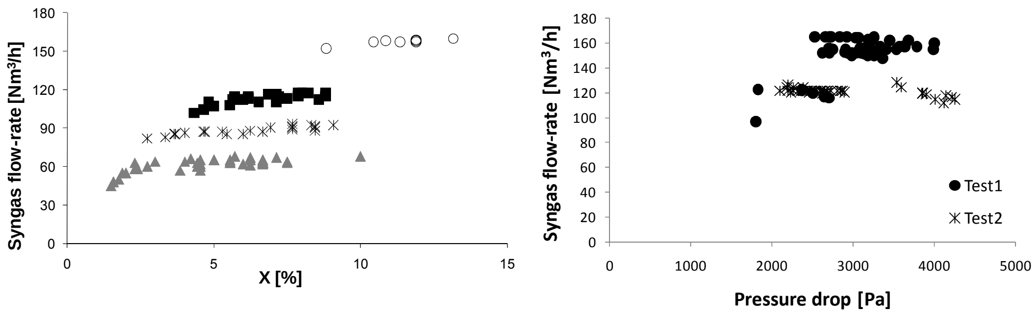

Figure 4: Syngas flowrate versus X ratio during the gasification of vine prunings (left) and versus the pressure drop during the gasification of corn cobs (right)

ticles with size >100 mm. All the size reduction methods gave a lot of dust (>30%) and a final size distribution again not complying with the specifications of Table 1. It had a quite high ash content (4.65%wt dry), a medium heating value (17 MJ/kg) and low density (110 kg/m^3). No surprise that, being a material unsuitable for the gasifier, the experimental campaign was stopped after two short runs. The material showed a strong tendency to form bridges in the gasifier hopper, thus it was not possible to feed it to the gasifier properly. Even more problematic than the case of vine prunings, these accidents were imputed to the presence of long sticks and the low bulk density of the biomass. During the short periods of working, the pressure drop resulted low (100-150 Pa) with low syngas flowrate (60-80 Nm^3/h). The X ratio was high (20-36%) denoting a high permeability of the bed to the air flow, thus giving high equivalent ratios and wide oxidation zones inside the gasifier. Therefore the heating value of the syngas was low.

4. Discussion

A detailed characterization of the fuel (proximate and ultimate analysis, calorific value) is important to evaluate the suitability of a biomass for the downdraft gasifier. It is necessary to determine whether the feedstock can provide enough energy and a sufficient amount of fixed carbon. The latter parameter indicates the possibility to form a char bed, which provides carbon for the gasification reactions, mechanically supports the above material and assures the air flow. These two last points are important for the proper operation of the gasifier, therefore the feedstock should be characterized also for its size and shape distribution, bulk density, thermal and mechanical consistency. Fine particles reduce the void fraction, by reducing the bed permeability to air and leading to a low syngas production and even reactor obstruction. Long particles (in the case of Gastone, it means sticks >100 mm) may compromise the feeding system and form bridges inside the reactor that enhance the bed permeability switching to combustion regime. Bridging is likely to occur in the feeding hopper, where long particles may form a stable layer for the accumulation of further material. In addition, the lower is the density of the biomass, the higher is the tendency to form bridges, as the weight of the biomass above the bridge is not enough to break the structure (Mattssonn 1997). This tendency was higher for vine prunings than wood pellets, since the latter one was characterized by shorter particles (60 mm) and a higher density (650 kg/m^3) compared to the former one (280 kg/m^3). The corn cobs had a more homogeneous size distribution giving good operations. The Miscanthus showed the highest bridging tendency, due to the large amount of oversized particles and the very low bulk density.Besides the feedstock characterization, it is necessary to monitor the pressure drop across the bed. High pressure drops indicate a low bed permeability, with a consequent reduction of the syngas production or even obstruction of the gasifier. On the other hand, low pressure drops indicate a too high bed permeability, or presence of by-pass channels, with a poor mixing between the gas and solid phases, resulting in a low biomass conversion. A low pressure drop may also indicate a low biomass content within the gasifier, with the gasification process switching to combustion (as in the case of rice husks). A very loose feedstock, such as Miscanthus, leads to very low pressure drops, thus indicating a high permeability of the bed and a high equivalence ratio. As a consequence, the heating value of the syngas is low. On the other hand, even if pellets are suitable for gasification in their original shape, they showed a low mechanical resistance as they turned to dust giving a high pressure drop and low bed permeability. These conditions reduced the syngas productivity and biomass conversion. These features are likely to be critical issues for the use of biomass pellets in downdraft gasifiers, since gasification systems based on fixed beds (Dasappa et al., 2011) operate in optimal conditions when producing syngas without building up a resistance that could reduce the syngas productivity. The representation in Figure 5 is semi-quantitative as the limits depends on the reactor configuration, efficacy

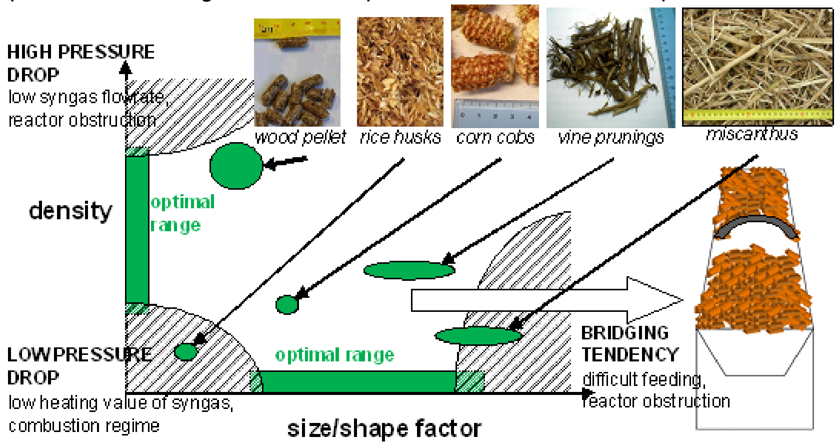

Figure 5: Specifications on the morphological and density properties of the feedstocks used in the tests described in this work for the safe operation in the downdraft gasifier

of pretreatments and some technical adjustments for assuring the continuous operation of the plant. The critical zones are highlighted with the possible accidents (e.g., low conversion, bridge formation, reactor obstruction, bed combustion).

5. Conclusions

The experimental results of the recent campaigns on biomass fuels at the CRIBE gasification plant are described and discussed in this paper. The biomass properties are related to the technological operations and plant performance. The feedstock size and shape distribution, bulk density, thermal and mechanical consistency, are crucial for the proper operation of the gasifier. The results of the tests are used to give further specifications on feedstock parameters (density and size/shape). Finally, the results of the tests will be used to study the entire process and evaluate the global efficiency, thus including the energy needs and mass loss in the pretreatments used to assure the safe operation of the plant. The development of a process model of the entire plant is in progress and will be used to evaluate the efficiency in different scenarios (e.g., electricity production, cogeneration) and study the effect of the feedstock characteristics.

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