Biomass gasification: experimental and modelling activities at CRIBE

M. Simone¹, E. Biagini², C. Nicolella¹, L. Tognotti¹

¹. Chemical Engineering, Industrial Chemistry and Material Science Department - Università di Pisa - ITALY
². Energy and Environment Division – Consorzio Pisa Ricerche- ITALY

1. Introduction

Biomass gasification can be operated in various reactor configurations and under different operating conditions. The process is versatile as for biomass input as well as for the product (electricity, cogeneration, syngas, hydrogen, Fischer-Tropsch fuels) and it is an option to promote distributed power generation. Despite this technology was proposed and studied starting from the mid 20th century, it is still not widespread due to some technological barriers that need to be addressed [1]. The major technological barriers can be classified in two groups:

a) gasifier feed specifications;
b) gas clean-up.

The former group represents the discrepancy between the properties of the harvested biomass and the gasifier specifications. For instance, even a small scale downdraft gasifier requires strict specifications related to the moisture content, the size and shape of the fuel, or even the charring behaviour of the biomass. As a consequence the gasification process loses its potential feed flexibility and demands additional conditioning treatments (drying, milling, screening etc.). The second group highlights the difficulties faced in finding a suitable gas clean-up process; the main issue of this group is the tar removal from the syngas. The syngas scrubbing with water just moves the tar problem from the gas clean-up to the wastewater treatment and reduces the process energy efficiency due to gas cooling. Advanced options such as tar cracking are widely investigated but are not adopted in commercial applications. These technological barriers can be removed by providing data from practical applications in order to demonstrate the feasibility of this technology even in a rural context. To this purpose a pilot scale gasification plant has been developed as part of the CRIBE biorefinery located in S.Piero (Pisa) [2]. The paper highlights the testing capabilities (feeds, gasifying agent and gas clean-up) and the information that can be obtained from this test rig.

2. Experimental activities

2.1. Gasification Plant Description

GASTONE is a gasification plant based on a 200 kWth downdraft gasifier which was installed and commissioned in March 2010. The nominal input of the gasifier is 50 kg/h of biomass with a maximum moisture content of 20%. Fig. 1 shows the flow-sheet of the plant: the chipped biomass is charged to the gasifier via a screw conveyor controlled by a level sensor inside the gasifier. The plant is operated slightly below atmospheric conditions due to a fun-blower positioned at the end of the cleaning line. As consequence air enters the gasifier...
from the environment through four nozzles positioned just above the throat of the gasifier. The biomass is supported on a moving grate at the bottom of the gasifier. As the gasification reactions proceed the biomass becomes smaller in size and the biomass residues (vegetal charcoal) fall under the grate, the charcoal discharge frequency can be regulated by means of the control panel. The charcoal is washed away from the bottom plate with running water to a settling tank and recovered with a screw conveyor. The produced gas moves upward from the bottom of the gasifier in an external ring and enters the clean-up system. The clean-up system consists of a cyclone, a venturi scrubber, a chiller-condenser, two sawdust filters and a bag filter. After the cleaning the gas is destined to a flare. The gasifier is designed to operate with biomass materials which must meet the specifications reported in Table 1. As aforementioned in the introduction the biomass specifications of the gasifier are quite strict compared to the conditions after the harvesting. One critical point is the moisture content of the biomass (<20%), thus a drying system has been installed to test several biomass materials.

Fig. 1  Flow-sheet of the gasification plant “GASTONE”.

Table I: Gasifier feed specifications.

<table>
<thead>
<tr>
<th>Moisture [%]</th>
<th>LHV [kcal/kg]</th>
<th>Ash [%]</th>
<th>Size 8-63 mm [%]</th>
<th>Size 3.15-8 mm [%]</th>
<th>Size &lt;3.15 mm [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>&gt;4350</td>
<td>&lt;3</td>
<td>88-100</td>
<td>0-10</td>
<td>0-2</td>
</tr>
</tbody>
</table>

The gasification plant GASTONE is equipped with in field pressure measurements to monitor the absolute pressure at the nozzles exits and the gas outlet in the gasifier, as well as the pressure drops in the condenser and in the filters. Four thermocouples are positioned along the clean-up line to evaluate the gas temperature at the gasifier exit (T0), at the cyclone outlet (T1), after the scrubber (T2) and just after the blower (T3). A data-logger transmits the temperature signals to a PC which displays the values and records the temperature history. The gas flow-rate can be monitored by a flow-meter positioned on a by-pass between the blower and the flare. The gas produced from the plant can be continuously sampled after the blower and analyzed with a portable Micro-GC which determines the volumetric composition of the gas and is interfaced with a PC for signal analysis and data recording. Several sampling and measure devices are under development:

- a sampling probe to extract solid samples from the gasifier bed and evaluate the temperature inside the gasifier;
• a tar sampling system based on a suction line which brings the gas into a series of cooled impingers in order to estimate the tar content of the gas and identify the tar tracer compounds with further analysis;
• a FTIR spectrometer that will extend the range of detectable gas species.

2.2. Tar Cracking Rig Description
As mentioned in the introduction, one of the main problems associated with biomass gasification is the tar production. A possible solution is the catalytic cracking of tar, in this case the syngas exiting the gasifier enters fixed beds filled with catalyst at high temperature where tar are decomposed to smaller compounds. To this purpose a lab-scale tar cracking-line named TAREK (Figure 2) has been developed. It is based on two fixed bed catalytic reactors (reactors diameter DN65, bed length 400 mm) and can be connected to the gasification plant just before the scrubber, to sample a small amount (5 Nm3/h) of the gas from the clean-up line. TAREK can also be operated stand-alone to allow carrying out tests independently of GASTONE. In this case a small cylindrical reactor positioned in an electric heater can be used both for biomass pyrolysis tests as well as for organic liquids evaporation.

![Fig. 2 Tar cracking line “TAREK” in stand-alone configuration.](image)

The guard bed is designed to be loaded with mineral material such as dolomite or olivine. The main bed is designed to support a metal catalyst (i.e. nickel). Both the guard bed and the main bed are positioned into cylindrical electric heaters to guarantee an accurate temperature control. TAREK is equipped with thermocouples and pressure indicators to monitor the temperature before and after every step of the treatment and the pressure drops through the beds. In addition three gas and tar sampling connections are available to evaluate the gas composition via Micro-GC and FTIR and the tar content.

2.3. Testing Capabilities
The aim of the experimental activities is the identification of biomass-residues mixtures which can be used in the gasifier, thus minimizing the fuel conditionings and expanding the range of applicable fuels. Fig. 3 reports the methodology for the design of such mixtures. The grey area represents fuel specifications required by the gasifier (ideal biomass). The red line represents the properties of a fuel which cannot directly be applied in the gasifier. After the identification of a suitable integrative biomass and its sharing (i.e. the amount of woodchips...
that have to be added to chicken manure) a new mixture (yellow line) which meets the gasifier specifications is obtained.

![Diagram of suitable biomass-residues mixture for the gasification process.](image)

**Fig. 3** Design of suitable biomass-residues mixture for the gasification process.

A further objective of the facility will be to study the effect of O2 enriched air on the gasification process (i.e. the tar abatement and moisture allowed). The tar-cracking line TAREK will allow studying the effectiveness of different catalysts, verifying the influence of the real syngas on tar cracking and optimizing the operating conditions for this process.

### 2.4. Preliminary results

The gasification plant operated successfully for 10 hours with wood pellets (Moisture 9\%, Ash 1.97\%, LHV>4350 kcal/kg). After three hours the gasifier reached a stable regime with a gas flow rate of 90-100 Nm\(^3\)/h, this condition was maintained for more than an hour, subsequently the gas flow-rate was modulated in order to estimate the maximum output of the plant (155 Nm\(^3\)/h). Fig. 4a shows the temperature histories of the four thermocouples of the clean-up system. The gasifier outlet temperature ranges from 330°C (stable condition) to 405°C (maximum flow-rate), the cyclone is not insulated so gas loses approximately 100°C before entering the water scrubber where it is dramatically quenched to nearly 30°C; finally the gas reaches nearly 45°C because it is heated in the blower. The plant is specifically designed to operate with wood chips; the nominal conditions for wood-chips are 180 Nm\(^3\)/hr gas flow-rate with 200-250 mmH\(_2\)O pressure drop across the bed. However wood pellets were chosen due to their low moisture content. This led to some operating issues. First wood pellets are three times heavier than woodchips, as consequence the biomass loading tank could not be completely filled to avoid the screw conveyor blockage. In addition wood pellets produce a lot of fines in the gasifier due to mechanical and thermal stress. As consequence the pressure drop across the bed doubles the nominal value related to woodchips. This leads to a reduction of the maximum gas flow-rate achievable from the plant. This is reported in Fig. 4b shows the gas flow-rate against the pressure drop through the bed. The gasifier produced good quality syngas as reported in Table 2, independently of the gas flow-rate. The values are in agreement with literature sources [2] regarding air blown biomass gasification in downdraft gasifiers. Notably the methane content is more than 2\% and C2 can reach 0.8\%, this may indicate a relatively high tar production. This is likely to take place with wood-pellet since the high production of fines and the high pressure drop may lead to the formation of preferential channels in the gasifier bed, thus reducing the tar cracking reactions.
Table II: Composition and lower heating value of the syngas.

<table>
<thead>
<tr>
<th></th>
<th>H₂ [%]</th>
<th>CO [%]</th>
<th>CH₄ [%]</th>
<th>CO₂ [%]</th>
<th>N₂ [%]</th>
<th>C₂ [%]</th>
<th>LHV [MJ/Nm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.4-13.8</td>
<td>20.2-25</td>
<td>2.3-3.9</td>
<td>11-16.3</td>
<td>44.5-48.3</td>
<td>0.4-0.8</td>
<td>4.8-5.2</td>
</tr>
</tbody>
</table>

Fig. 4-(a) Temperature histories in the clean-up line of the gasification plan; Fig. 4-(b) Gas flow-rate as a function of the pressure drop through the gasifier bed.

3. Modelling activities

The experimental work on the facility is integrated with numerical activities in order to provide a comprehensive understanding of the effect of the operating parameters. The purpose of the modelling activity is to produce a diagnostic tool to support the experimental activities. The modelling methodology is based on a hierarchical problem decoupling to enhance the reliability of all the “blocks” of the model structure [4]. The modelling approach (reported in Fig. 5a) schematizes the gasifier as a 1-D distributed domain (only the axial variable distributions are represented) meshed with 300-1000 cells. Both the gas and the solid phases are taken into account and their fluidodynamic is represented with PFR reactors. The system is simulated with the software gPROMS. The simulation of the system requires operational input (gas and solid flow rates, wall temperature), gas and solid compositions and some details about the pyrolysis behaviour of the biomass (devolatilization kinetics, microproducts distribution and gas species). The model is based on dynamic equations of heat and mass balance; therefore the ignition behaviour can be simulated as well as variations in the operating conditions. The main outputs of the simulation are the gas species and the temperatures distributions along the gasifier axis. Figure 5b shows the gas and solid temperatures in the gasifier during the gasification of woodchips for two values of the equivalence ratio. Notably the higher the ER, the higher the maximum temperature of both phases. Three different zones can be observed in the thermal profile:

- the solid phase is heated up by the radiation from the lower hot zone; consequently the gas phase is heated up by convective heat transfer from the solid phase;
- the temperature peak is caused by the oxidation reactions that mainly rise the gas temperature;
- after the oxidation reactions the temperature decreases due to gasification reactions and thermal dispersion; in this zone the gas and solid phases reach a thermal equilibrium.
Further results of this detailed approach are the rate of char conversion due to char oxidation and gasification which is a useful information to estimate the reaction front position. The probe mentioned in section 2.1 will allow validating this information.

Fig. 5-(a) Modelling scheme of the downdraft gasifier; Fig. 5-(b) Results of the downdraft gasifier model (effect of Equivalence Ratio on the temperature of solid and gas phases).

4. Conclusions and further developments

The CRIBE is pursuing several activities related to the study of biomass gasification. The aim of these activities is to help this technology to overcome the technological barriers that halt its commercial diffusion (feed flexibility, gas clean-up). To this purpose a pilot-scale gasification rig (GASTONE) was installed. GASTONE is a commercial plant so it was necessary to enhance its analytical performance (thermocouples, gas and tar sampling and detection systems) in order to convert it into a scientific facility and the gasifier flexibility (in terms of acceptable feedstock and operating conditions) will be one of the first issue that will be addressed by the experimental campaign. In addition a side-stream tar cracking line will be developed to provide data about the catalytic cracking in practical conditions. The experimental activities are coupled with numerical simulations to gain a deeper insight in the gasification process and understanding the effect of the operating conditions.

5. References