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## Production of gaseous carriers via biomass gasification for energy purposes

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### Abstract

It is under development a biomass gasification plant based on a 1 MW<sub>th</sub> bubbling fluidized bed (BFB) reactor with internal recirculation. Compared to conventional BFB design, the mechanism of internal circulation of solids can give beneficial effect to the process in terms of biomass conversion efficiency into gaseous product and gas quality. A model describing the process of biomass gasification in the two reaction chambers was developed. Expected results were preliminarily validated by experimental results obtained at a bench scale facility working on the same gasification concept.

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*Keywords:* Biomass; Gasification; Biofuels; Bubbling fluidized bed; Process modeling.

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### 1. Introduction

Lignocellulosic biomass is considered one of the most promising renewable energy sources (RES) for the targets the EU wants to achieve by years 2020 and 2050. As known, the two deadlines respectively concern the so called 20-20-20 targets, and the reduction of greenhouse gas emissions at 80-95% below 1990 levels [1]. Though very ambitious, the attainment of such a goals will allow the full development of a energy system with low environmental impact based on the widespread use of RES.

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Many are the processes that can be considered for the production of energy from biomass, among these, the thermochemical process of gasification is one of the most interesting thanks to the versatility of employments in which the produced gas can be used. Starting from a solid fuel, the gasification process makes possible to produce a gaseous energy carrier very flexible that can be used for combined heat and power (CHP) production, or as intermediate, and further conversion, for production of derived energy carrier such as: H<sub>2</sub>, SNG and biofuels.

In the short to medium term, the technology of biomass gasification in fluidized bed reactors, compared to others, appears to be the most promising for many of the above mentioned applications since it is suitable for continuous operation and process scalability over a large range of sizes [2].

In the present work it is reported the activity concerning the development and scale-up of an improved bubbling fluidized bed (BFB) gasifier. Compared to BFB reactors of conventional configuration, in the new gasifier the bed inventory is not just fluidized, but it is also involved in a mechanism of internal recirculation. This arrangement gives a better gas-solid contact and an higher residence time of the fuel particles under the reaction conditions. Therefore, thanks to the synergy of the two effects, the quality of the produced gas can be improved in terms of higher gas yield and reduced organic contaminant load. Preliminary tests of steam/oxygen gasification carried out at a 10 kW<sub>th</sub> bench scale facility working on the same gasification concept, provided very promising results [3].

Taken into account the specific characteristics of the designed reactor, a gasification model describing the biomass gasification process in the 1 MW<sub>th</sub> ICBBFB gasification reactor has been defined. In this paper the attention has then been focused on the development of the model and on its preliminary validation on the basis of the experimental results obtained at the bench scale facility.

#### Nomenclature

BFB	bubbling fluidized bed
CHP	combined heat and power
CRF	char reactivity factor
DME	dimethylether
ER	equivalence ratio
ICBBFB	internally circulating bubbling fluidized bed
RES	renewable energy sources
SNG	substitute of natural gas
U <sub>ufc</sub>	fluidizing velocity in the up-flowing chamber
U <sub>dfc</sub>	fluidizing velocity in the down-flowing chamber
WGS	water gas shift

## 2. The internally circulating bubbling fluidized bed gasifier

The internal circulation of the bed inventory is obtained by means of a vertical baffle plate located in the bottom part of the reactor. The plate separate the reactor in two interconnected area, reaction chambers, at which the gasification medium is fed at different flow rate. Thanks to the opening present at the base of the baffle and at the difference in the fluidizing velocity realized in the two chambers, a circulation movement of the bed inventory is thus induced and sustained over time. In Fig. 1 a sketch of the gasifier design and of the above described operating concept are presented.

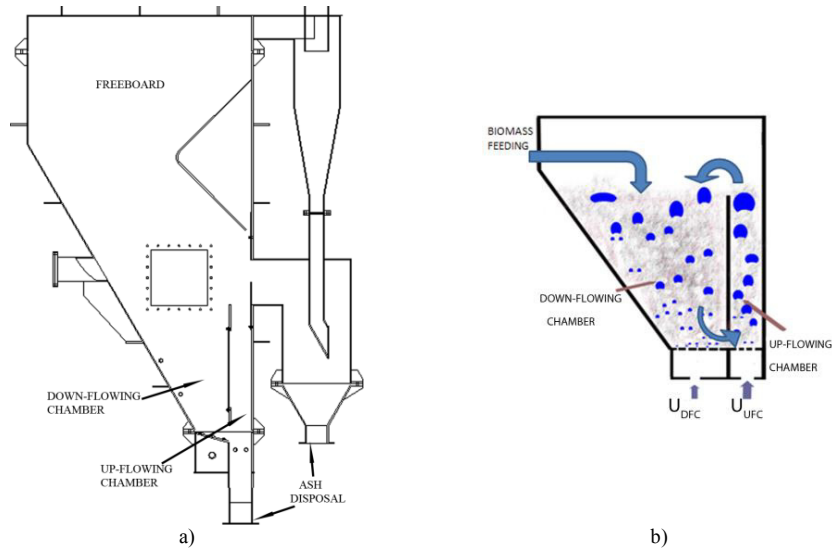


Fig. 1. a) Sketch of ICBFB gasification reactor; b) internal circulation bed inventory principle.

Based on this concept, at the Enea-Trisaia Research Centre it is under development a  $1\text{MW}_{\text{th}}$  ICBFB gasification pilot plant. In Fig. 2 a sketch of the whole plant is shown.

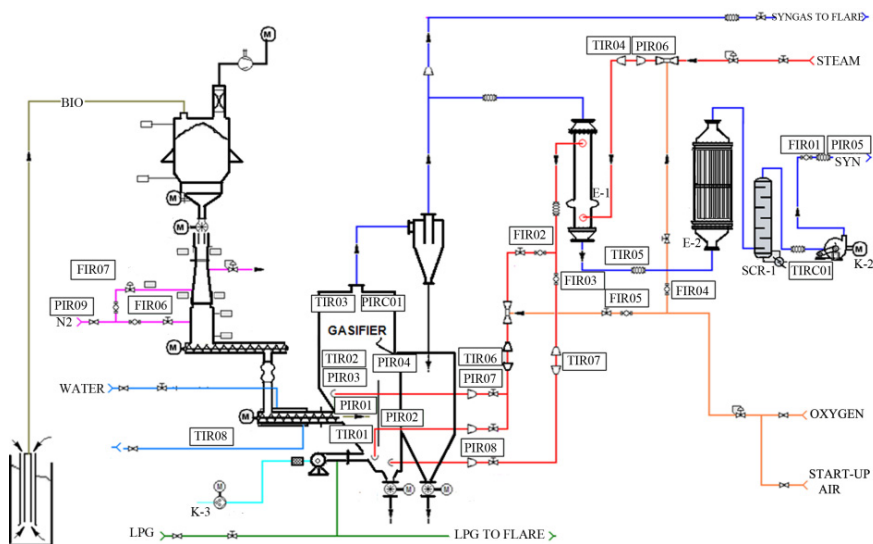


Fig. 2. Scheme of the  $1\text{MW}_{\text{th}}$  pilot plant.

The plant is intended to prove and validate the gasification process at a size such as to be useful for further scale-up and industrialization. To this aim it is fully equipped for on-line parameters monitoring and acquisition. Moreover it is designed to maximize the efficiency of the process through integrated energy recovery, and produce a cleaned gaseous stream ready to be use in CHP application or, after adjustment of the final composition, for production of advanced energy carriers as for instance: Fischer-Tropsch biofuels, Methanol, DME, SNG and  $\text{H}_2$ .

As indicated in Fig. 2, the gasifier is integrated with section for downstream gas cleaning where the produced gas is treated in order to remove entrained particles, through a cyclone, and tar contaminants via biodiesel wet

scrubbing. The plant is operated at atmospheric pressure and uses a steam/enriched air mixture as a gasifying medium to produce a gas of medium heating value. Use of oxygen is also possible.

### 3. Modeling of the biomass gasification process at the 1MWth ICBFB gasifier

To study the dependence of the gasification process from parameters such as: equivalence ratio (ER), steam/biomass (S/B) and hydrodynamic conditions inside the reactor, a simplified model of the biomass conversion into gasification products was considered and implemented through the commercial chemical process simulation software CHEMCAD (*Chemstations<sup>TM</sup>*). The process was modeled considering the four known process steps occurring in a general process of autothermal biomass gasification (i.e. drying, pyrolysis, gasification and combustion) [4]. In order to take into account the specific design of the ICBFB reactor, namely the presence of two interconnected reaction chambers with different reaction environments, some of the reactions involved in the conversion process were considered predominantly occur in one of the chambers rather than the other. A simplified representation of the gasification reactions considered and related areas of occurrence in the reactor is shown in Fig. 3, together with the corresponding specific layout of simulation. In accordance with the main steps and reactions to be modeled, the operation units considered in the process layout were then:

- biomass dryer
- stoichiometric reactor for the reactions of pyrolysis
- kinetic reactors for reactions of gasification and combustion of the pyrolysis products
- kinetic reactor for the adjustment of the gas composition via water gas shift (WGS)
- kinetic reactor for the combustion of methane and reactions involving this gas
- heat exchangers to account for: energy balance inside the reactor, between the solids (biomass, char and bed inventory) and the produced gaseous species; heat losses across the wall reactor.

In the same layout schema, biomass, steam and enriched air were considered as input chemical species, whereas char, water, tars and permanent gases ( $\text{CO}$ ,  $\text{H}_2$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2$ ) were considered as outputs.

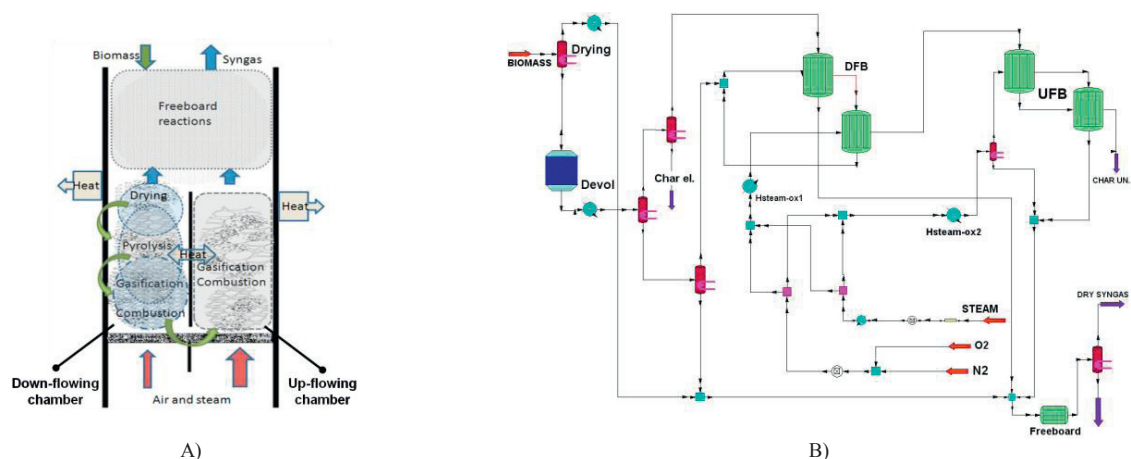
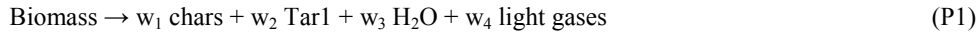


Fig. 3. Representation of the gasification reactions in the ICBFB reactor (A) and corresponding process layout of modeling (B).

As inferred by the figure, the biomass is fed into the down-flowing chamber of the reactor where it undergoes a first drying. The drying is considered an instantaneous process and in the simulation layout is modeled as a simple separator unit where it is provided the heat necessary to evaporate and heat up both the moisture and the biomass feedstock up to the reactor conditions. Pyrolysis is the second step of the process; since it is known to be a much faster process than gasification, the assumption that the pyrolysis is an instantaneous process is adopted. As a consequence, the gas released during this step mixes with the up-flowing gas stream (gasifying agent and the gas

released from char gasification). In the course of this stage, char, tar, a mix of permanent gases (i.e. CO, H<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>) and water are produced. The formation of such products is generally modeled in accordance with the following biomass decomposition path:



where *Tar1* indicates a vapor mix of several organic molecules which composition depends on the specific operating condition. Normally this mix of products is indicated as primary tar and, under the typical conditions realized in a process of biomass gasification, quickly undergoes further reactions and decomposition, thus producing additional amount of permanent gases and more stable organic compounds, known as tar as well. Below it is reported the reaction path describing the primary tar decomposition:



The relative amounts of pyrolysis products have been extensively described in literature [5-9]. It is well known that the yield of the products obtained in this step are dependent from several process parameters such as: temperature, heating rates and residence time of the produced components under the reaction conditions. Reactor configuration can also have effect. In the case of fluidized bed the coefficients  $w_j$  and  $y_i$  in the general reaction are chosen considering the yields distribution as a function of particle diameter and fluidized bed temperature [8-10].

As far as biomass, char and tars are concerned, some assumptions were actually adopted about their composition. Specifically, taking into account the elemental analysis of the almond shells used in the tests at the bench scale, for the biomass feedstock it was calculated a pseudo-formula corresponding to CH<sub>1.60</sub>O<sub>0.68</sub>; for char it was adopted the assumption it was composed of only carbon, and finally for tars fractions, the two mixes of compounds were identified with only two molecules. Primary tars were identified with methoxybenzene; according to reaction path (2) this compound was supposed to undergo a thermal cracking with production of CO and CH<sub>4</sub>, and formation of only naphthalene [11]. This latter molecule was assumed as representative compound of *Tar2* since it is known to be the most abundant tar compound presents in syngas from fluidized bed gasifier. In the modeling, under the typical conditions present in the down-flowing chamber of the reactor, the naphthalene conversion was assumed to be 75% and give formation of light gases and soot [12]. According to data from literature, at the considered process temperature the yield of char residue produced at the end of the step of biomass pyrolysis was set equal to 20% by weight, while the tar yield was set equal to 10-15% by weight. [13, 14]. The two decomposition reactions were simulated with stoichiometric unit. Combustion and gasification of the pyrolysis products occurring in the two chambers of the reactor, together with the water gas shift reaction, were simulated with kinetic units that provide essential information on kinetic mechanisms of the involved reactions. In Table 1 a summary of the main heterogeneous and homogeneous reactions in relation to these last two steps and considered in the model is presented.

Table 1. Heterogeneous and homogeneous reactions considered in the model of biomass gasification in the ICBFB reactor.

Chemical reactions	Frequency Factor	Activation energy	$\Delta H_R$ (kJ/mol)	Rate Equations Ref.
R1 $C + \frac{1}{2}(1 + \psi)O_2 \rightarrow \psi CO_2 + (1 - \psi)CO$	$5.67 \times 10^9$	160	-393 ( $\psi=1$ )	(15)
R2 $C + H_2O \rightarrow CO + H_2$	15170	121	+131.4	(5)
R3 $C + CO_2 = 2CO$	36.1	77.3	+172.6	(5)
R4 $C + 2H_2 \rightarrow CH_4$	$41.89 \times 10^{-4}$	19.2	-75.0	(5)
R5 $CH_4 + H_2O = CO + 3H_2$	$73.01 \times 10^{-3}$	36.15	+201.9	(5)
R6 $CO + H_2O = CO_2 + H_2$	2.78	12.6	-41.2	(16)
R7 $CH_4 + 2O_2 = CO_2 + 2H_2O$	$9.2 \times 10^6$	80	-808.5	(16)
R8 $H_2 + 0.5O_2 \rightarrow H_2O$	$10 \times 10^{11}$	42	-241.7	(16)

In the bottom part of the reactor, the produced char reacts with the oxygen in the gasifying agent provided at the reactor inlet; here only the reactions of char are considered to occur. The produced char is assumed to be either partially or completely oxidized to form CO and CO<sub>2</sub>, respectively, as indicated in reaction R1[15]. In the process simulation the ratio CO/CO<sub>2</sub> is calculated from the equation:

$$\frac{(1-\psi)}{\psi} = 40000 \cdot \exp(-15106/T)$$

In particular for the up-flowing chamber, due to the excess of oxygen, it is considered  $\psi=1$ .

Reaction R2 represents the steam gasification of carbon. It is the main endothermic process occurring at this stage, together with the *Boudouard* reaction (R3) which converts the carbon dioxide in carbon monoxide. Though in some conditions reaction R2 is slightly faster, in the model herein developed the rate of these two reactions were considered similar.

Reaction R4 represents the formation of methane through the hydrogasification of char. Differently from the reactions R2 and R3, involving char as well, being exothermal this reaction is favored at low temperatures. However its incidence on the process is also strongly related to the reactivity of the produced char and H<sub>2</sub> partial pressure: to obtain high yields of methane at constant temperature, fast heating and high pressures are required. Methane formation via R4 reaction occur simultaneously to its reaction of steam reforming (R5). Thus, the net production of methane depends on the relative reaction rate of R4 and R5. At medium-high temperatures ( $T > 500^{\circ}\text{C}$ ), the steam reforming reaction is faster than methanation, on the contrary when the process temperature is low ( $T < 500^{\circ}$ ) the favored reaction is methane formation. Due to such behavior, the methane content in the produced gas is often considered a signal of the real conditions realized in the reactor. In particular, a high content of CH<sub>4</sub> in the syngas is an index of a drop in the temperature realized inside the gasifier, which in turn suggests the process is being run under anomalous operating conditions.

When the temperature is sufficiently high ( $T > 800^{\circ}\text{C}$ ), in the presence of high amounts of water and carbon monoxide, the water gas shift reaction (R6) will take place. With regards to the gas composition of the final gas produced, the reaction of WGS is one of the most relevant with respect to the composition, and therefore to the quality of the final produced gas.

The last reactions considered in the modeling were reactions R7 and R8. They are both exothermal and therefore are useful to guarantee the autothermicity of the process, however, they are in some way undesirable as imply a consumption of useful gas products. As indicated by the respective equations, in both this reaction it is involved oxygen, which is fed to the two reaction chambers at different flow rate, therefore the right compositions of the gasifying mediums provided to the two reaction chamber of the gasifier is a parameter with important consequences on the quality of the produced gas.

### 5.1 Heat transfer and Energy balance

An important difference between chars from biomass and from fossil fuels (e.g. coal) is their reactivity. Specifically, in the case of biomass it was found that char reactivity increases with the conversion degree, while that of char from coal decreases [16]. Therefore the char reactivity is a key aspect of the gasification process. It significantly depends on parameters, such as: char porosity, number of active sites and biomass particle size. In order to take into account this aspect, some authors introduce in their kinetic equations pre-exponential factors corrected by a constant. This constant is generally known as *char reactivity factor* (CRF) [17, 18].

In the model presented in this work, the CRF coefficient was considered a parameter and, keeping fixed operating conditions such as: gasifying agent, temperature, and pressure, its effect on the quality of the produced gas and energy balance of the reactor was studied. A summary of the obtained results is presented in Table 2.

The simulated data showed that by increasing the CRF coefficient, a better gas composition is obtained, since it becomes richer in H<sub>2</sub> and CO. However it has to be considered that as the CRF value increases, the temperature within the reactor drops very rapidly due to the fact that the gas undergoes endothermic reactions in the down-flowing chamber. Therefore, if the same flow conditions are kept, the combustion reactions in the up-flowing chamber becomes critical for the energy balance of the entire reaction. In order to make autothermal the entire

biomass gasification process, the enthalpy exchanged as heat among the different components (gases, bed inventory and biomass), the processes taking place in the ICBBF gasifier and the surroundings have to be properly addressed. Specifically, the heat output produced in the combustion reactions, has to balance the heat needs required in all steps of materials heating-up and drying (i.e. biomass, bed inventory, produced gases), decomposition reactions and thermal losses.

Table 2. Simulation results with different value of *char reactivity factor* (CRF)

ER=0.33 S/B=0.5		CRF		
		1	10	100
Dry gas composition (%v)	Hydrogen	34.8	36.0	36.4
	Oxygen	0.0	0.0	0.0
	Carbon Monoxide	25.6	28.2	29.2
	Carbon Dioxide	34	30.7	29.5
	Nitrogen	0.0	0.0	0.0
	Methane	5.2	4.7	4.5
	Water (g/Nm <sup>3</sup> )	531	447	421
Tar (C <sub>10</sub> H <sub>8</sub> ) (g/Nm <sup>3</sup> )	10.7	9.75	9.45	
Gas Yield (Nm <sup>3</sup> /kg <sub>bio, daf</sub> )	1.25	1.37	1.42	

In the process modeling under development, the heat losses were calculated in a simplified way, considering a uniform temperature (gas and mineral matter) inside the reactor, a global convective-radiative heat transfer coefficient,  $h_w$ , and the entire external area of the reactor. At steady state conditions the global energy balance of the reactor can then be written as:

$$H_{\text{comb}} = -H_{\text{heat loss}} + H_{\text{bio}} + H_{\text{steam-ox}} + H_{\text{drying}} + H_{\text{pyrol}} + H_{\text{gasific}} - H_{\text{elut}} - H_{\text{product gas}}$$

With a CRF greater than 1 the model predicts an excessive char consumption in the gasification reactions and the combustion reaction in the up-flowing chamber does not have sufficient char to furnish the heat ( $H_{\text{comb}}$ ) necessary to the entire process. In order to avoid the occurrence of such kind of restriction, a CRF equal to one was fixed.

Taking into account the minimum hydrodynamic conditions to be met for good fluidization and circulation of mineral in the bed and the energy balance in the entire reactor, a sensitivity analysis was made by varying the flow rates in the two chambers in order to optimize their O<sub>2</sub>/steam ratios with respect to the dry gas composition and tar content. Three values were explored, specifically: 0.25, 0.5, 1. In Table 3 a summary of the results obtained from the sensitivity analysis is presented:

Table 3. Simulation results for different values of oxygen/steam molar ratio supplied to the up-flowing chamber.

ER=0.33, S/B=0.5		Oxygen/steam		
		0.25	0.5	1 <sup>a)</sup>
Dry gas composition (%v)	Hydrogen	32.2	33.3	34,8
	Oxygen	0	0	0
	Carbon Monoxide	24.2	25	25,6
	Carbon Dioxide	37.4	35.8	34
	Nitrogen	0	0	0
	Methane	5.8	5.5	5,2
	Water (g/Nm <sup>3</sup> )	577	551	531
Tar (C <sub>10</sub> H <sub>8</sub> ) (g/Nm <sup>3</sup> )	61.4	42.7	10,7	
Gas Yield (Nm <sup>3</sup> /kg <sub>biom, daf</sub> )	1.16	1.20	1,25	
Char out (g/Nm <sup>3</sup> )	2.7	12.2	37,2	

a) Oxygen/steam molar ratio relevant to the experimental conditions.

By comparing the data, it appears evident that with the same ER and S/B the results of simulation are quite similar. This happens because the kinetic reactors are supposed to work always in an isothermal condition ( $T = 855$  °C) and temperature decrease in the reactor due to difference with respect to the considered experimental condition are not taken into account. To maintain the reactor bed at this temperature, the same flow rate as in the experimental test is needed to be sent at the two chambers.

#### 4. Experimental set-up at the 10 kW<sub>th</sub> ICBFB gasification plant

The bench scale facility is based on a 10 kW<sub>th</sub> reactor working with the previously described gasification concept of internal circulation of solids. This reactor has an internal diameter of 134 mm and a height of 791 mm. The vertical plate is 320 mm high; when in operation, the bubbling bed is approximately as high as the separating plate, therefore under the effect of different mass flow rates between the two chambers, a circulation of the mineral bed and solid fuel is produced. The facility is also equipped with sections for gas cleaning (i.e. cyclones, ceramic candle filter and wet scrubbing) in order to provide experimental results on the whole process chain, as the facility is also intended for more general purposes. In Fig. 4 a detailed schema of the 10 kW<sub>th</sub> facility is shown.

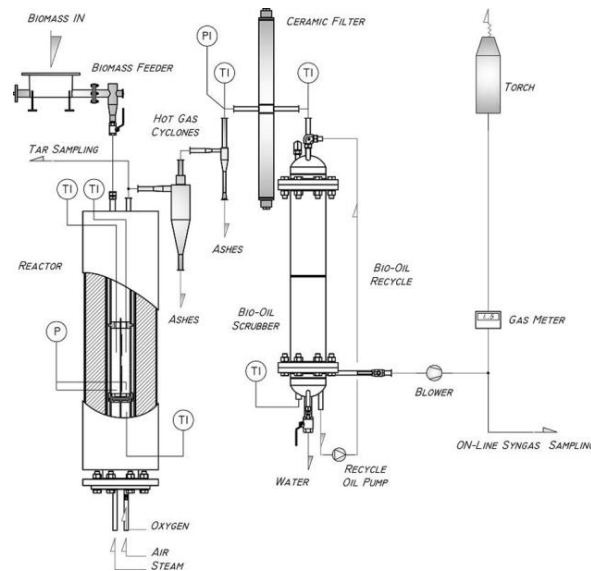


Fig. 4. Schema of the 10 kW<sub>th</sub> ICBFB gasification plant

The gasification medium injected to the gasifier is obtained by mixing oxygen and water steam, pre-heated up to about 400 °C. To approach the minimal condition for the start-up of the gasification process, before feeding the biomass into the bed inventory, the reactor is heated up to the desired gasification temperature by means of an external electrical oven and a stream of hot air. This latter is also allowed to flow through the bed inventory and the downstream piping. The temperature attained through the line is normally not lower than 300 °C. When the starting conditions are stabilized, the steam-oxygen mixture is injected at the ER and S/B ratios to be investigated. In the meantime the feedstock mass flow is gradually increased up to the test value. At the exit of the gasifier, the produced raw gas flows through two cyclones and a ceramic filter candle for particle removal. The filtered gaseous stream is then sent to a wet scrubber for tar removal. Piping and equipment from the gasifier outlet to the scrubber inlet are carefully insulated to avoid thermal dispersion and tar condensation. The dry gas produced is measured by a gas meter downstream to the scrubber; a vacuum pump is used to suck the gas through the plant. To evaluate the gasification process, after reaching the steady-state conditions, the process stream is sampled in order to have indications about the dry gas composition and contents of: tar, water and particulate. At the end of the gasification run, char residue and product gas yield are also evaluated.

##### 3.1 Materials and Methods

To carry out the gasification tests at the 10 kW<sub>th</sub> gasification facility almond shells were selected. This biomass feedstock is a typical example of residual biomass that can be profitably valorized for energy purposes. It is particularly indicated for exploitation via gasification since it has a significant energy density. Moreover it can be supplied to reactors of different design as it is, without needs of any additional pretreatment (e.g size reduction,



densification etc). It is worth to mention that though the results herein presented were obtained testing a specific biomass feedstock, their soundness is still of general validity and therefore can be considered of reference for the process under development, independently from the specific biomass considered. Almond shells were selected just for convenience, being easily available in the area where the gasification plants are located. Process and technology under development will be applicable also to other kind of raw materials.

A summary of the main physical and chemical properties of the biomass feedstock is presented in Table 4.

Table 4. Characterization analyses of almond shells feedstock

Proximate analysis (% wt <sub>dry</sub> )		Ultimate analysis (% wt <sub>dry</sub> )				Heating Value (MJ/kg <sub>dry</sub> )	
Ash	1.65	Carbon	47.8	Oxygen <sup>b)</sup>	43.68	High heating value (HHV)	20.2
Volatile Matter	77.90	Hydrogen	6.38	Chlorine	0.018	Low heating value (LHV) <sup>c)</sup>	18.7
Fixed Carbon <sup>a)</sup>	20.45	Nitrogen	0.44	Sulphur	0.028		

a)  $FC = 100 - (\%VM + \%Ash)$

b)  $\%O = 100 - (\%C + \%H + \%N + \%Cl + \%S + \%Ash)$ , dry basis

c)  $LHV (kJ/kg) = HHV (kJ/kg) - (24.41 \times 9.836 \times \%H)$

As far as the bed inventory is concerned, it was used a commercial olivine supplied from *Magnolithe GmbH*. The plant was operated under the process conditions of: 855°C, atmospheric pressure, 0.5 steam/biomass (S/B) and 0.3 ER ratios. The selected biomass was supplied at a feeding rate of 0.75 kg/h.

### 3.2 Samplings at the ICBFB gasification plant

Dry gas composition was measured by sampling the produced gas downstream of the gas meter via an on-line gas-chromatography system Agilent Technologies (HP 6890 Series) equipped with proper column for permanent gas analysis and a TCD detector. The identification and quantification of each component was based on retention time and multilevel external calibration, respectively. The tar load in the product gas was measured according to the CEN/TS 15439 procedure. Briefly, after having sampled the gas for about 200 N litres (dry basis) the gas sampling was stopped and the 2-propanol solutions contained in impinger bottles were all mixed in a single Erlenmeyer flask. The tar solution was then treated for GCMS analysis. The chromatographic analysis was carried out with GCMS system Agilent Technology-Mod. 5975 B. When needed, the solutions were properly diluted with fresh solvent. For tar molecule identification and quantification multi standard solution, containing up to 24 molecules, were used.

The water content in the syngas was measured on amounts of the 2-propanol tar sampling solution via Karl Fischer titration. Finally, the char residue in the gasifier was determined by combustion. At the end of each test, oxygen was supplied to the gasifier in order to promote the char combustion. In the course of reaction, the carbon dioxide production was monitored over time via an on-line infrared detector. Oxygen was supplied until complete disappearance of CO<sub>2</sub> in the exhaust gas stream, and then stopped.

## 5. Results and discussion

At the operating conditions adopted, the tests of steam/oxygen gasification of almond shells provided a gas yield of 1.2 Nm<sup>3</sup><sub>dry</sub>/kg<sub>daf</sub> with a dry composition of: 28-30%v H<sub>2</sub>, 24-26 %v CO, 34-36 %v CO<sub>2</sub>, 6-8 %v CH<sub>4</sub> and 4 %v light hydrocarbons (i.e. C<sub>2+</sub>). For this produced gas it was then evaluated a corresponding calorific heating value in the range 10-12 MJ/Nm<sup>3</sup><sub>dry</sub>. At the exit of the reactor, the gas showed a water content of about 400 g/Nm<sup>3</sup><sub>dry</sub> and a total chromatographic tar content of 10 g/Nm<sup>3</sup><sub>dry</sub>. Aromatic compounds belonging to many classes were present, from single ring compounds, such as toluene and phenol, up to multi condensed rings such as benzo[g,h,i]perylene. However, among these compounds, naphthalene was found to be the most abundant, with a concentration accounting for about 50% by weight. Finally, from the stage of combustion carried out at the end of each gasification test, char residue up to a maximum value of 42 g/Nm<sup>3</sup><sub>dry</sub> was estimated.

By recalling the results obtained from the process modeling in relation to char reactivity (see Table 2) and dependence of the considered reactions from the composition of the gasifying medium (see Table 3), the comparisons with the experimental results obtained at the bench scale facility appear to be in quite good agreement. For the main permanent gas components the highest differences in the compositions were found in relation to

hydrogen and methane. However for these two components complementary discrepancies were actually found, thus indicating that part of the hydrogen expected to be released as  $H_2$ , although minimal, still remains chemically bounded in the light hydrocarbons, such as  $CH_4$ . For this latter it is in fact known that its reforming is very sensitive to the operating condition at which the gasification process is carried out. Significant agreement was also found in the comparison of data relevant to the char residue and tar content.

## 6. Conclusions

Within the limitations related to the different scale of reference, the experimental results about gas compositions, both dry and wet, tar content, char residue and dry gas yield were found to be in good agreement with the corresponding expected outputs, calculated with the developed predictive model. This agreement thus provided a good evidence that the adopted sets of conversion reactions involved in the biomass gasification at the ICBFB gasifier under development are the most relevant.

The comparison gives a preliminary validation of the model developed to describe the process of biomass gasification at the 1 MW<sub>th</sub> pilot gasifier. Better indication about the validity of the gasification process as currently shaped, and in case on the proper modifications to be implemented, will be certainly obtained from the experimental gasification test at the pilot plant. This campaign will be started soon.

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