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Steam/oxygen biomass gasification at pilot scale in an internally circulating bubbling fluidized bed reactor

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ABSTRACT

An innovative 1000 kW_{th} pilot plant based on a bubbling fluidized bed gasifier with internal recirculation was operated in experimental campaigns of biomass gasification. The evaluations were focused on the gasifier performances and quality of the product gas. To this aim, tests were carried out at atmospheric pressure using almond shells as a feedstock and three defined gasification mediums (i.e. steam/O_2 mixture, 35wt.% and 50wt.% O_2 enriched air); process temperature was in the range 820–880 °C.

The result assessment allowed to evaluate the system flexibility to the gasifying agent and acquire data on the gas producible with this specific configuration. Based on the dry compositions, LHVs in the range 5.9–6.7 MJ/Nm^3_{dry}, 6.3–8.4 MJ/Nm^3_{dry} and 10.9–11.7 MJ/Nm^3_{dry} were respectively calculated for the three product gases. Correspondingly, an increase in the cold gas efficiency from 0.5 up to 0.7 was also estimated. Concerning the contaminant loads, in the case of the tests related to steam/O_2 biomass gasification, particle and tar contents were found in the range 6–10 g/Nm^3_{dry} and 12–18 g/Nm^3_{dry}, respectively, while H_2S, HCl and NH_3 were at concentrations below 100 ppms (v).

1. Introduction

Lignocellulosic biomass is considered as an important source for the achievement of the goals the European Union has defined on energy, environment and sustainable development issues. As known in relation to these themes, two deadlines have been set for the year 2020 and 2050. The first one concerns the known “20–20–20” targets contained in the climate and energy package, which aims to ensure that the European Union meets by 2020 the three key objectives of a 20% reduction in greenhouse gas emissions from 1990 levels, raising the share of energy consumption produced from renewable resources to 20%, and finally a 20% improvement in the energy efficiency [1]. The second one instead concerns the roadmap the EU has set out in order to reach the objective of reducing Europe's greenhouse gas emissions by 80–95% compared to the 1990 levels and thus moving to a competitive low-carbon economy in 2050 [2]. Though very ambitious, the achievement of such goals will represent the EU successful contribution to the emission reductions of GHG to hold the global warming below 2 °C, compared to the temperature in pre-industrial times.

Many processes can be considered for the production of energy from biomass [3–12], among these, the thermochemical process of gasification is one of the most interesting due to the versatility of uses that the product gas can be addressed. Starting from a solid fuel, the gasification process allows to produce a very flexible gaseous energy carrier that can be used for combined heat and power (CHP) production by using the product gas in internal combustion engine (ICE), gas turbine (GT) and fuel cell (FC), or as intermediate and further conversion for production of derived energy carrier such as H_2, SNG and biofuels [13–25]. In the short to medium terms, 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 as it is suitable for continuous operation and process scalability.

Bubbling fluidized bed (BFB) reactors have characteristics that make them advantageous with respect to fixed bed gasifiers. Such reactors have in fact larger tolerance to the particle sizes of the supplied feedstock, good control of the process temperature, uniformity of the reaction environment, and scalability at larger sizes. At the same time, higher simplicity in construction and operation, longer residence time of the fuel particles under the process condition and reduced particle entrainment, are some of the main aspects that can also give BFB gasifiers a certain advantage compared to reactors of fast circulating fluidized design. However when biomass is the considered feedstock, in the BFB reactors a certain tendency of the fuel to remain at the surface of the bed inventory can occur.

Such tendency is strictly correlated to the particle density of the supplied feedstock, and it clearly represents a disadvantage as it can bring a lower conversion efficiency of the fuel in gaseous products and a higher entrainment in the product gas of particles from the feedstock and the

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generated char. The difficulty in maintaining the biomass particles inside the bed affects the performance of gasification. Process conditions at the surface of the bed (i.e. temperature, heat transfer and solid–gas contact) are less favorable to the reaction kinetics of char gasification and tar conversion than those inside the bed. The use of a reactor with interconnected chambers can overcome such disadvantages allowing for movement of the solid particles inside the bed, counteracting their tendency to segregate the bed surface and, at the same time, reducing the phenomenon of elutriation.

Kuramoto et al. in their works [26,27] used an interconnected fluidized bed having the aim to improve the movement of the solid particles inside the bed, Snieders et al. [28] used similar devices to test the circulation of pellets and Abellon et al. [29] to determine the residence times of glass beads in a four-compartment interconnected fluidized bed. Foscolo et al. [30] in their tests with a cold model rig proved that a sufficient circulation of the bed inventory allows for a prolonged residence time of light fuel particles within the bed and avoids segregation to the bed surface.

Experimental tests were conducted by Freda et al. [31] to study the fluidization and to measure the recirculation of glass spheres inside the solid material of the bed in a cold model apparatus. In a recent work numerical simulations were implemented by Canneto et al. [32] to study the fluidization quality and the circulation of the solid between the two chambers of a cold model reactor.

Zhou et al. [33] studied the effect of different fluidization velocities on rice husk circulation rate. Zhi [34] reported good temperature homogeneity throughout the top and bottom zones of each bed of an interconnected fluidized reactor during sawdust gasification tests in a pilot plant. Xiao et al. [35], using animal-waste-derived, conducted experimental tests in an internally circulating fluidized-bed, with separated gasification and combustion reaction zones. A recent review [36] provides a comprehensive and up-to-date survey of the state of the art of the fluidized bed reactors, including the gasifiers with internal (and external) circulation of the solid material.

Based on such concept, at Enea-Trisaia Research Centre (Italy) a gasification pilot plant of 1000 kW_{th} rated power was built. In this paper the activity carried out at this pilot plant and the preliminary results achieved during the early experimental campaigns of biomass gasification are presented. These tests were aimed at evaluating the operability of the pilot reactor and the performance of the biomass gasification process.

For the mentioned process, steam/oxygen is the gasification medium of reference, however during this experimental campaigns, tests with enriched air were also included. Such tests were considered in order to evaluate the flexibility of the process to gasification agents, collect data on the gas composition obtainable at the specific plant and operating conditions, and at the same time assess the beneficial effect of using steam/oxygen as gasification medium. Moreover, the use of oxygen-enriched air as gasifying agent may have some advantages compared to the gasification carried out with air. Keeping constant the thermal input of the gasification plant, the reduced amount of nitrogen in the gasifying agent, can in fact allow operating the gasification process with a reactor, and related equipment for full plant operation, of reduced sizes with consequent decrease in the required capital investment costs. The production of a gas with a higher LHV can also have an effect on the internal combustion engine. In fact, the availability of such a fuel gas can enable the use of smaller and cheaper internal combustion engines. Moreover, the availability of a technology based on enriched-air gasification can make it suitable for RDF gasification [37,38], thus expanding the fields of its applicability. Studies on low cost technology for oxygen-enriched air production are giving an important sustenance to the feasibility of such applications [39–42].

Soon after completing the stage of process evaluation in the above-described configuration, the pilot plant will be implemented with an innovative cleaning system that will integrate the steps of gas filtration and conditioning directly into the reactor vessel. The ultimate result will be a more compact and effective technology that will enable the achievement of better process performances and reductions of investment costs.

2. Experimental set-up

2.1. The 1000 kW_{th} gasification pilot plant

The working principle of this reactor is based on the concept developed by Kuramoto et al. [26,27] in relation to circulating fluidized particles within a single vessel. At each chamber, the gasifying agent is provided at different fluidizing velocities and this allows the particles of the bed material to move from one sector to the other, and recirculate around the baffle plate throughout the interconnecting orifice. The circulation of the bed particles is then sustained over time as long as the difference in the gas velocity of the fluidization medium at the two chambers is maintained [30]. A sketch of the gasifier design is presented in Fig. 1.

Compared to a conventional bubbling fluidized bed configuration, the gasifier with internal recirculation (ICBFB) can favor the process of gasification in terms of the yield and quality of the product gas (e.g. reduced tar load). Experimental tests and numerical simulations of fluid dynamics made with a cold model have in fact shown that different ratios of fluidization velocity between the up-flowing and down-flowing chambers result in different circulation rates of the bed material between the two chambers. A higher circulation rate can give rise to a deeper and more effective sinking of the biomass particles in the bed material, as well as to a more uniform temperature of the bed itself [31,32]. Therefore, when in operation, the mechanism of internal recirculation is expected to counteract the tendency of the fed biomass to segregate over the surface of the bed. In the same way, also the elutriation of the produced fine carbon particles is reduced. These factors all favor the yield and quality of the product gas by providing a high temperature environment, a higher residence time of the fuel particles under the reaction conditions and therefore an overall improvement of the thermo-chemical reactions involved. Tests of steam/oxygen gasification were preliminarily carried out at a 10 kW_{th} ICBFB bench scale facility and provided very promising results [43].

Thereafter, based on the same concept, a 1000 kWth ICBFB gasification pilot plant was also built. The facility is intended to demonstrate and validate the gasification process at a significant scale, thus collecting data useful for the further steps of scale-up and industrialization. In such perspective, the plant is fully equipped for on-line acquisition and monitoring of key process parameters, such as temperatures, pressures and flow rates. In Fig. 2 a sketch of the whole plant is shown.

According to the figure, the plant was designed to maximize the efficiency of the process through integrated energy recovery, and to produce a cleaned gaseous stream ready to be used in CHP production. To this aim, downstream of the gasifier, the plant also consists of sections for heat recovery and gas cleaning where the product gas is treated to pre-heat the gasifying agent and to remove entrained particles and tar contaminants, respectively.

For the process under development, the steam/oxygen mixture was selected as the gasifying agent of reference in order to have a product gas with a near-zero nitrogen content. Therefore, in addition to the cogeneration applications, after proper adjustment of the final composition and compression, the gas producible at such plant could also be considered for conversion into gaseous or liquid secondary energy carriers, such as H_2, SNG, Fischer–Tropsch biofuels, methanol, and DME.

2.2. Gasification test campaigns

As indicated above, the 1000 kW_{th} pilot plant is designed to operate with steam/oxygen as the main gasifying agent, however the use of oxygen-enriched air is also possible. In order to evaluate the flexibility of the system to the gasification medium and acquire data on the gas

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