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Air–steam gasification of biomass in a fluidised bed: Process optimisation by enriched air

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ABSTRACT

The effect of oxygen concentration in the gasification agent was studied by enriched–air–steam biomass gasification tests in a bubbling fluidised-bed gasification (FBG) plant. The oxygen content in the enriched air was varied from 21% (v/v, i.e. air) to 40% (v/v), aiming at simulating FBG where enriched air is produced by membranes. The stoichiometric ratio (ratio of actual to stoichiometric oxygen flow rates) and steam-to-biomass ratio (ratio of steam to biomass, dry and ash-free, flow rates) were varied from 0.24 to 0.38 and from 0 to 0.63, respectively. The tests were conducted under simulated adiabatic and autothermal conditions, to reproduce the behaviour of larger industrial FBG. The temperature of the inlet gasification mixture was fixed consistently at 400 °C for all tests, a value that can be achieved by energy recovery from the off-gas in large FBG without tar condensation. It was shown that the enrichment of air from 21 to 40% v/v made it possible to increase the gasification efficiency from 54% to 68% and the lower heating value of the gas from 5 to 9.3 MJ/Nm^3, while reaching a maximum carbon conversion of 97%. The best conditions were found at intermediate values of steam-to-biomass ratio, specifically within the range 0.25–0.35. The enriched-air–steam gasification concept explored in this work seems to be an interesting option for the improvement of standalone direct air–blown FBG because it considerably improves the process efficiency while maintaining the costs relatively low as compared to oxygen-steam gasification.

1. Introduction

Gasification is a promising technology for biomass and waste utilisation with low environmental impact, reducing global CO_2 emissions. Standalone air-blown bubbling fluidised-bed gasification (FBG) is the simplest and probably the most cost-effective concept for medium-scale thermal and electricity applications (<5–10 MW_e). It has been successfully demonstrated connected to a large coal-fired boiler in power plants, resulting in high efficiency when burning biomass. For small-scale power production a unit comprised of a gasifier and a compression-ignition engine is less expensive than a boiler-based power cycle, thus providing an attractive option for remote locations [1].

The use of air in gasification yields a fuel gas highly diluted by nitrogen. The lower heating value (LHV) of the gas is therefore typically below 6 MJ/Nm^3. The use of steam has proven effective for achieving a medium heating value (up to 14 MJ/Nm^3), but the process becomes more complex. Two different concepts have been developed, for full-scale steam gasification: steam-oxygen mixtures and indirect gasification based on twin-bed reactors [2].

In steam-oxygen gasification the biomass is partially oxidised to provide the heat necessary to make the process self-sufficient. The gas produced has a high hydrogen content and the dilution of nitrogen is avoided. This concept has been extensively tested at laboratory scale [3,4], but the high cost of pure oxygen (for instance, based on distillation units) makes the implementation of this process uncertain at industrial scale [5].

Indirect biomass gasification is based on the separation of the gasification and combustion stages in two different chambers. The heat supply to the gasification process, which is fed with steam, is generated in the combustion chamber, in which the char is burnt out using air. The heat transfer is achieved by circulation of the bed inventory between the two stages. The essential contribution of this concept is that it allows 'autothermal' steam gasification without the need of oxygen (only air is used), producing a gas with medium heating value, i.e., not diluted by nitrogen. This technology has achieved semi-commercial status today [6,7].

Much experimental work has been done on FB biomass gasification using different gasification agents. Air [8], pure steam [9–11], oxygen-steam [3,4] and air–steam [12–14] tests have been carried out in various lab-scale facilities, generating useful knowledge for understanding the process. Relatively little work has been found, however, using enriched–air–steam mixtures as gasification agent [15]. Moreover, most studies at laboratory or pilot scale have been conducted allothermally; the temperature, air/oxygen-to-biomass ratio and

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steam-to-biomass ratio have been varied independently because the temperature of the gasifier is controlled by external heat addition using electric heaters. However, this method of supplying heat is neither technically nor economically feasible for large-scale implementation, so the results from "allothermal" lab-scale rigs must be interpreted with caution.

In previous work [16], we have studied the process improvement by using air–steam mixtures under simulated adiabatic and autothermal conditions. We have shown how the optimisation of air–steam mixtures in autothermal FBG increases the gasification efficiency from 40% to 60%, while maintaining the low heating value of the gas at around 5 MJ/Nm^3. The process was, however, limited to using air as the source of oxygen to the system, i.e., 21% (v/v).

In this study we have extended the previous work by allowing the oxygen to vary in purity up to 40% (v/v) in the enriched air. This higher figure was chosen because it is the oxygen concentration that can be produced using commercial air separators based on membrane technologies. This way of producing oxygen would keep the investment and operational costs relatively low compared to processes that need pure oxygen, usually based on distillation units. Consequently, the size of plants where this concept is expected to be feasible is not necessarily large. Therefore, the concept investigated in this work could be convenient for medium-scale electricity production (<5–10 MW_e), provided the gas cleaning, particularly tars, is done properly. This study looked at gas quality and the impact on carbon conversion and process efficiency. Tar production and cleaning strategies will be addressed in future work.

The tests were conducted varying the flow rates of biomass, steam and enriched air and the oxygen concentration in the enriched air, making it possible to explore the effects of these variables on the quality and composition of the produced gas, aiming at process optimisation. All the tests were conducted with wood pellets in a pilot-scale FBG simulating autothermal and adiabatic conditions. In addition, the temperature of the gasification agent was fixed at 400 °C for all tests, a value that can be achieved by energy recovery from the off-gas without tar condensation. With this experimental setup, we expect that the results will be useful for scaling up the data to design industrial FBG, i.e., large standalone direct gasification units without external heat supply and with low wall-heat loss.

2. Experimental

2.1. Materials

The biomass used was wood pellets with the empirical formula $CH_{1.4}O_{0.64}$ (dry and ash-free, d.a.f.) [16]. The moisture and ash content were 6.3% and 0.5% (w/w), and the lower heating value of the fuel (as received) was 17.1 MJ/kg. The pellets were cylindrically shaped with a mean diameter of 6 mm and 5–10 mm long. The apparent density of the pellets and the bulk density were 1300 and 600 kg/m^3. The bed material used was ofite, a sub-volcanic rock composed mainly of feldspar, pyroxene and limestone, whose complete characterisation is given in [17].

2.2. Facility

Fig. 1 shows the layout of the facility and Table 1 gives the main parameters of the pilot plant. The rig has been described in detail in a previous publication [16]. The only modifications made in the plant with respect to previous work were the erection of a plant for oxygen production and the removal of the tar scrubber to avoid tar condensation in the pipes between the cyclones and the combustion chamber. In addition, the pipes were maintained at a temperature above 400 °C by heating elements and insulation blankets. The oxygen plant comprised four 10-m^3 oxygen bottles, making it possible to produce 10 Nm^3/h with a purity higher than 99%.

2.3. Test procedure

The protocol for the tests was similar to that used in [16]. Therefore, only a brief description is given here.

At the beginning of each test a batch of bed material (around 8 kg) was added to the reactor. The bed was heated up with the hot air and the electric heater. The bed and the freeboard were rapidly heated up to approximately 700 °C. It was necessary, however, to wait longer before starting the biomass feed in order to avoid tar deposition on the pipes between the cyclones and the combustion chamber. Once the temperature upstream of the combustion chamber was higher than 300 °C, the facility was considered ready for biomass, and biomass was fed slowly into the reactor. In these conditions of oxygen excess, the biomass was oxidised completely and the reactor was rapidly heated to the desired process temperature. From the beginning of the test, a computer-based data acquisition system monitored and recorded the temperatures, pressures, gas composition (H_2, CO, CO_2, CH_4, O_2), power supplied to the heating equipment and the flow rates of gas and solid. The transition from combustion to gasification was made by increasing the biomass flow rate to decrease the air-to-biomass ratio. The steam addition started once a steady-state condition was established. The mixture of steam and air was heated in a preheater and then fed to the FBG. Once the process condition was stable, the oxygen was added to the steam before mixing with air, with the flow rate reduced to an appropriate value to obtain the desired level of oxygen in the final mixture. The final air–steam–oxygen mixture was heated in the preheater to the process temperature (400 °C). In all tests an initial transitory period of 3 to 4 h was followed by a steady-state period of 5 to 7 h. The operation was finalised by taking a sample from the bed inventory and combusting the remaining char in the bed. After each test, the two cyclone bins and the extraction-ash bin were sampled and analysed.

2.4. Operating conditions

The mode of operation we used for conducting the tests (adiabatic tests and temperature of inlet gasification mixture fixed at 400 °C) for a given biomass (wood pellets) consisted of four variables that could be independently varied: the flow rates of biomass, air, steam and oxygen. The flow rates of air and oxygen determined the oxygen content in the enriched air inlet, i.e., the O_2 purity (hereafter referred to as OP, in % v/v).

For a given biomass flow rate, two ratios can be defined for the analysis of the process: (1) the stoichiometric ratio (SR), defined as the mass ratio between the amount of total oxygen fed in and the stoichiometric amount of oxygen required for combustion, and (2) the steam-to-biomass ratio (SBR), defined as the flow rate of steam fed to the reactor divided by the biomass flow rate (dry and ash-free). Two additional variables must be taken into account: (3) the oxygen percentage of the enriched air (OP), which is an indication of the nitrogen dilution of the produced gas, and (4) the biomass throughput. However, for a limited range of this parameter in an FB, the system can be analysed approximately by a mean of (1), (2) and (3), as the biomass flow rate is expected to have a minor influence on the results.

The experimental program comprised tests with air–oxygen–steam mixtures in different proportions. In the first set of tests, air was used as oxygen supplier, so the OP was 21% v/v for all tests and the oxygen flow rate was nil. Some of these tests have been reported in previous work [16]. The second set of tests involved air–oxygen-steam mixtures in which the OP of the enriched air was set at 30, 35 and 40% v/v. Some of these tests were conducted twice to ensure the reproducibility of the results.

The experimental programme comprised tests varying SR, SBR and OP between the indicated ranges: SR from 0.24 to 0.38, SBR from 0 to 0.63 and OP from 21 to 40%. To establish these ratios, the following flow rates were varied between the indicated ranges: the steam flow