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Comparison of inorganic constituents in bottom and fly residues from pelletised wood pyro-gasification

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HIGHLIGHTS

- The residues of pelletised biomass pyro-gasification have been studied.
- The residues represent 10% of the biomass (bottom 96%, fly 4%).
- The inorganic elements are distributed in different quantities in the two residues.
- In general, the heavy metal content of the two residues is very low.
- The organic S of the biomass is found in the exhaust fumes of the engine as SO_2.

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ABSTRACT

Wood biomass is a source of renewable energy and is now recognised as a potential alternative for sustainable energy production. During the pyro-gasification process, the mineral components of the biomass accumulate under the grate of the pyro-gasifier (bottom residue) or become volatile and are deposited as fly residue in the cyclone filters. This work analyses the constituents of the two residues produced by the pyro-gasification process of pellets in a pilot scale downdraft system. The residues are composed of char and ash. The ash makes up 7% of the bottom residue and 38% of the fly residue. The Ca, Mg, Na, S, P, Si and Cu contents in the two residues are almost comparable. Fe, Al, Cr, Zn, Ni, Pb, Cd, Mn and B are concentrated in the fly residue. Potassium is a particular case and is present in low concentration in the fly residue. The mass balance has revealed that some elements can pass the first filtration phase (cyclones) and they are trapped in the gas which must be successively cleaned. Therefore, knowledge of the composition of the biomass (macro and microelements), and of the behaviour of their transformation products, is important for the plant design and functioning. It is also equally important for the disposal or the utilisation of the solid by-products.

1. Introduction

An increase in global energy demand has exacerbated the problem of fossil fuel resource depletion. Wood biomass is a source of renewable energy and is seen as a potential feedstock for sustainable energy production. Gasification process is a form of thermo-chemical conversion that transforms solid biomass into gaseous fuel through a partial oxidation at high temperatures (900/1200 °C). The gas obtained from the gasification (syngas) (CO, H_2, CH_4, etc.) can be used for the generation of electricity and heat [1,2]. However, this gas contains many impurities, such as particulates, ammonia, hydrogen sulphide, hydrogen chloride, alkali metals, metals, and organic compounds ranging from light hydrocarbons to tar.

With regard to the above, some studies have dedicated particular attention to investigate the main internal and external factors that affect gasification performance: the type of gasifier, the operating conditions and the biomass properties [3]. The main types of gasifier are fluidised bed, entrained flow bed and fixed bed. There are two types of fixed-bed gasifier, which are suitable for small scale applications: downdraft and updraft. The downdraft gasifier has the advantage of generating a low tar content syngas, thus facilitating the gas cleaning phase for cogeneration [4,5].

Studies related to downdraft gasification systems have generally focused on the aspects of main gas composition, heating

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values, gas yield and gasification efficiency [4–11]. However, few investigations have focused on the behaviour of the mineral part of biomass during the downdraft gasification process [12–14]. In fact, in suitable operating conditions of the reactor, some species of the mineral components become volatile, carrying chlorine, sulphur, alkali, alkali earth metals and other elements either in the gas phase or in the form of condensable species. They may damage or clog pipes and de-activate catalysts [15,16]. Therefore, knowledge of the composition of the biomass (macro and microelements), and of the behaviour of their transformation products, is important for plant design and functioning, and also for the disposal or utilisation of process by-products.

The aim of this work is to identify the fraction of elements that deposit readily, and of those which follow the syngas stream, in relation to their content in the initial biomass. A pilot scale autothermal downdraft pyro-gasification plant has been used for this purpose. Preheated air at approximately 620 °C, together with wood pellets, is introduced from the top of the pyro-gasifier. The operating conditions of this plant ensure a fast heating of the biomass to generate a flash pyrolysis. After the gasification (1250 °C), the solid by-product that collects under the grate of the reactor is indicated in this work as bottom residue, and that which is trapped by the cyclones as fly residue.

2. Experimental

2.1. Pilot scale pyro-gasification facility

The diagram of the plant and related description is provided in Fig. 1. The configuration of the pyro-gasification plant is based on a continuous flow downdraft cycle in which a sub-stoichiometric quantity of air enters the top part of the pyro-gasifier together with the fuel. The plant is fuelled with commercially available wood pellets. The biomass feedstock is preheated to approximately 85 °C in order to reduce moisture content, and exploits the residual heat of the engine exhaust fumes (path not shown in the diagram). The air introduced is preheated to approximately 620 °C by the heat of the syngas exiting the reactor (Fig. 1). The preheated air plays an important role in the flash pyrolysis process which precedes the gasification stage. The temperature profile inside the reactor rises to a maximum of approximately 1250 °C, whereas in the medium low zone of the reactor the outlet temperature of the syngas is approximately 900 °C. The produced gas exits from the lower part of the reactor which is equipped with a rotating grate under which the solid bottom residue collects (point 3 in the diagram). The fly residue entrained by the syngas is trapped by two cyclones operating in series with particle cut sizes, d_{p50}, of 4.5 µm, and accumulates in a specific tank (point 4 in the diagram). After the cyclone filters the syngas is further purified, cooled, and sent to the engine, as shown in Fig. 1.

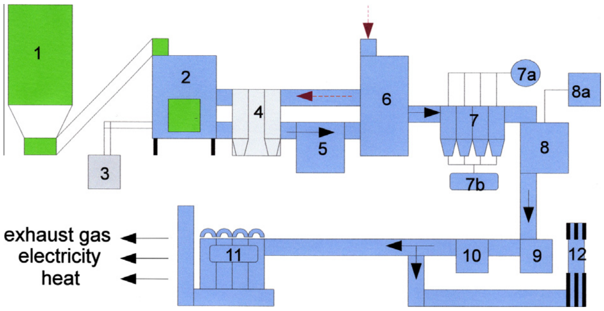

Fig. 1. Diagram of the plant: 1 – silos, 2 – reactor, 3 – ash and char deposit, 4 – cyclones, 5 – catalyst, 6 – heat exchanger, 7 – scrubbers with nebulised water, 7a – water pump, 7b – washwater deposit, 8 – gas cooler, 8a – cooling system, 9 – electrostatic filter, 10 – cartridge filter, 11 – engine, 12 – torch. The path of the air is indicated in red dashed line, the path of the syngas in black. The plant operates with a slight vacuum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

122.5 kg/h of pellets produce 11.8 kg of bottom residue and 0.49 kg of fly residue (mean values in 5 h of plant functioning). The gas produced is a mixture which consists of CO 17%, CO_2 15%, CH_4 16.5%, H_2 11%, O_2 0.5% and N_2 40% with a lower calorific value of approximately 2200 kcal/Nm^3. The hourly quantity of syngas produced is 300 Nm^3 and generates 250 kW_{el}.

2.2. Characterisation of the pellets

Moisture content, ash content, volatile matter and fixed carbon were determined. Moisture content was determined according to UNI EN 14774-2 standard (Solid biofuels – Determination of moisture content – Oven dry method – Part 2: Total moisture – Simplified method) and ash content was determined according to UNI EN 14775 standard (Solid biofuels – Determination of ash content). For the determination of volatile matter, the UNI EN 15148 standard (Solid biofuels – Determination of the content of volatile matter) was followed.

Elemental analyses were carried out by inductive coupled plasma atomic emission spectrometry (ICP-AES) (Perkin Elmer Optima 7000) except for mercury and arsenic which were conducted by cold-vapour AAS and Hydride-generation AAS respectively (Perkin Elmer MHS-20). 5 g of pellets (dry weight) were dissolved with 25 mL of conc. HNO_3 followed by 20 mL of H_2O_2 in a 250 mL flask and were maintained at boiling temperature until completely dissolved (except for insoluble silicate residues). The solution obtained, after filtering, was 50 mL. For the determination of total silicon, 5 g of pellets were incinerated at 550 °C and the resulting ash was melted with $LiBO_2$ at 900 °C. The melt was dissolved in dil. HCl. The solution was made up to a final volume of 50 mL. For the determination of non-volatile sulphur, 5 g of pellets were subjected to dry distillation at 550 °C and the distillation residue was incinerated at the same temperature. The resulting ash was dissolved in HCl 6 M, and the solution was made up to a volume of 50 mL. The solutions were then subjected to elemental analyses.

2.3. Characterisation of the residues

5 kg of the bottom residue was sampled in subsequent periods during the operation of the plant and reduced to the amount appropriate for analysis through the coning and quartering method. It was ground into fine powder and homogenised in a mortar. The fly residue, present in a much lower amount than the bottom residue, was collected at the end of the period of experimentation and analysed immediately. This was already in fine powder form suitable for analysis.

Moisture content was determined according to the standard procedure indicated for the pellets. Ash content was determined at two different temperatures. At 550 °C, as described in the standard procedure UNI EN 14775, and at 800 °C, according to the ISO 1171 (Solid mineral fuels – Determination of ash). The pH of both the residues and their ash, after combustion at 550 °C and 800 °C, was determined. The pH value was determined by suspending the sample in ultra-pure water with a solid/liquid ratio of 1:5 m/v (UNI EN 13037: Soil improvers and growing media– Determination of pH).

The elemental analysis was carried out by ICP-AES. The bottom and the fly residues (2 g each) were burnt at 550 °C and 800 °C for the purpose of eliminating the carbonaceous fraction (char). 0.1 g of ash from each residue was solubilised in 10 mL of HCl 6 M by heating. The determination of total silicon was carried out as previously described for the pellets.