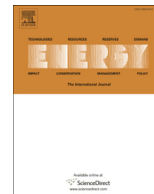




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Pressurized gasification of torrefied woody biomass in a lab scale fluidized bed

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ABSTRACT

This work reports experimental results concerning the influence of torrefaction level and pressure on product yields and composition during fluidized bed O₂/steam gasification of two different raw biomasses. The results show an increase in gas yield with pressure and torrefaction level for both types of biomass considered. Increasing pressure caused the produced gas composition to shift towards higher CH₄ and CO₂ content, while H₂ and CO levels decreased. The effect of the type of original biomass on gas composition was limited, and became less relevant as pressure and torrefaction level increased. The analysis of the tars produced during gasification also revealed that higher pressures led to the increase of tar yields. On the other hand, torrefaction level presented the opposite effect, with lower tar yields and lighter molecular weight distribution of tars as torrefaction level increased. Since torrefaction is being considered as a promising pretreatment technique for upgrading biomass to a higher quality solid fuel more suitable for the integration of gasification into biofuels production, the results from this study are relevant for evaluating the influence of the level of torrefaction on the performance of gasification under typical operating conditions in practical applications.

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1. Introduction

Nowadays, concerns about climate change effects and depletion of fossil fuels have drawn attention to find alternatives and more environmentally friendly ways of energy supply. Some of the major issues for fossil fuels are their non-renewable nature and the problems related to the release of pollutants (mainly CO₂, NO_x and SO_x) into the atmosphere [1], enhancing the global warming effect [2]. Despite that, fossil-derived fuels are the most common energy sources used in the world, reporting over 80% of the total energy consumption [3]. However, substantial efforts are being made on the development of alternative renewable energy sources that can replace the aforementioned fossil-derived fuels. In this context, biomass is reaching more positions and becoming one of the most widely used renewable energy sources. Biomass supplies about 15–20% of the total fuel use in the world [4], being currently the fourth largest resource of energy worldwide just after coal, oil and gas [5]. One of the

main advantages associated with biomass is its conventional neutral CO₂ impact, when produced in a sustainable manner. Furthermore, among all renewable energies, biomass is the only storable and transportable source and the only renewable source of carbon, hydrogen and oxygen, which makes it a prime feedstock for production of multiple bio-based products within the next 20–30 years. In this scenario, biofuels, particularly for the aviation and heavy-duty trucks, have been recognized as one of the main pieces in the bioeconomy puzzle, as these transport sectors are not likely to be electrified in the coming decades and biofuels is thus the only near-medium term alternative to fossil-derived [6,7].

Despite the great potential of biomass, its use presents also a series of challenges. Two main limitations are the space needed to grow it and the expensive cost of transportation due to its low energy density [8]. Other drawbacks are high oxygen and water content, and hydrophilic properties [9].

A pretreatment stage prior to biomass conversion is needed in order to minimize some of the abovementioned drawbacks. In this context, torrefaction seems to be an effective option. Torrefaction is a thermochemical process that subjects the biomass at a temperature in the range of 200–320 °C in an inert atmosphere achieving

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a higher energy-dense product (almost moisture free) which is more feasible for transport. Besides, previous studies have shown other advantages of this technology, i.e., the fact that not only improves energetic value but also enhances feedstock homogeneity, grindability and hydrophobicity [10–14].

Another key aspect when evaluating the use of biomass as energy source is the conversion technology. Biofuels can be produced from a broad spectrum of conversion processes (biological, thermal and physical processes). Among the thermochemical conversion technologies, gasification is perceived as the most promising pathway to improve the efficiency in the use of biomass towards liquid fuels [8,15].

Biomass gasification has been exhaustively studied [8,16–19], particularly regarding the producer gas composition and heating value. The syngas composition can be influenced by several process parameters such as feedstock composition and particle size, gasification conditions, mainly temperature, equivalent ratio (ER), steam to biomass ratio and pressure [16,19], but also by the gasification reactor design.

With regards to temperature, Gil et al. [17] studied the gasification of pine chips with steam–oxygen mixtures in a fluidized bed gasifier varying the temperature from 780 to 890 °C. The study concluded that the increase of bed temperature leads to an increase in H₂ content, H₂/CO and CO/CO₂ ratios, together with higher thermal efficiencies of the process. Other studies on fluidized bed gasification of woody biomass [20–24] also have concluded that the introduction of steam was favourable to improve gas quality and that higher temperatures favoured both hydrogen production and gas yield. However, it was stated that gasification temperatures above 850 °C decreased the gas heating value, mainly due to the reduction of CO, CH₄ and C₂ hydrocarbons in the produced gas.

Mayerhofer et al. [25] studied the gasification of wood pellets in a bubbling fluidized bed (BFB) varying several operating conditions (temperature, pressure and steam to biomass ratio (S/B)). The results showed that high temperatures (750–840 °C) promoted the formation of H₂, while CH₄ and CO₂ content decreased. Additionally, higher S/B ratios shifted the gas composition to higher concentrations of H₂ and CO₂ and lower contents of CO and CH₄ in the produced gas, which can be explained qualitatively with the enhanced water gas shift reaction. Lastly, pressure had a significant effect on the effluent gas composition [25]. For comparable temperatures and S/B, and increase in gasification pressure led to higher CH₄ content due to the enhancement of the methanation reaction at high pressures, together with a slight increase in H₂ content, and lower CO/CO₂ ratios.

The bibliographic revision denotes that although gasification is influenced by several other parameters, the two principal studied parameters have been temperature and ER. This fact evidences a lack of studies related to the effect of pressure and biomass feedstock properties (influenced by (i) feedstock nature and (ii) thermal pretreatments such as torrefaction level) on syngas composition.

The goal of this paper is to study the influence of pressure and biomass composition (by the gasification of two different biomasses at three different torrefaction levels: raw biomass, lightly torrefied and significantly torrefied), on product yields and composition during fluidized bed O₂/steam gasification. The obtained results will allow the evaluation of gasification performance in order to determine optimal operation conditions. Notice that the information here presented has been obtained in a lab scale gasifier, and although the main trends and conclusions of this study can be useful to give insight to the gasification of torrefied biomass, the actual numbers could be different in an industrial scale gasifier.

2. Experimental

2.1. Sample characterization and preparation

Norwegian spruce and Norwegian forest residues (mainly tops and branches), hereby referred as VW and GROT, respectively, were obtained from local sources in Trondheim, Norway. The original biomasses were treated at two different torrefaction levels: Lightly torrefied LT (final torrefaction temperature of 225 °C) and significantly torrefied ST (final torrefaction temperature of 275 °C). The raw samples and torrefied products were sieved to a particle size range of 250–500 µm. The proximate and ultimate analyses were carried out using a LECO Thermogravimetric analyzer (TGA 701) and a LECO TruSpec CHN–S–O analyser, respectively. The proximate analyses of all samples were conducted following the ASTM D7582 standard test method for moisture, volatile matter, and fixed carbon determination. The results together with the lower heating values (LHVs) are included in Table 1. The determination of the heating value of the samples was performed in an isoperibol LECO Automatic calorimetric bomb (AC600), according to the ASTM D5865-07 standard test method. After each measure the bomb was washed out with a 0.2 M KOH solution to recover sulphur (H₂SO₄), halogens (HCl, HF, HBr) and phosphorous (H₃PO₄), which were measured afterwards by ionic chromatography (Dionex ACS 1100) according to the EN-15408:2011 standard method.

2.2. Setup and procedure for torrefaction

Torrefaction experiments were performed using a bench-scale continuous reactor consisting of four independent horizontal conveyors positioned in parallel from top to bottom. Each conveyor consisted of a horizontal pipe (i.d.: 100 mm) with a screw conveyor that allowed a precise control of temperature and residence time of the different stages. Drying, heating and cooling conveyors had a length of 700 mm, whereas the torrefaction conveyor was 1000 mm long. The reactor, capable of operating at temperatures of up to 300 °C, had a capacity of 0.2–7.0 kg/h of biomass in size range of 1–25 mm. The feedstocks were first ground and afterwards compressed to produce pellets of 6 mm diameter without adding binders. These pellets were fed from the storage hopper to the first conveyor by a feeding screw, after that the fed material passed through the screw conveyors for drying, heating to torrefaction temperature, torrefaction and cooling and finally left by gravity to a collecting vessel. Notice that the material was transferred between conveyors using pneumatically controlled sliding valves. The conveyors were temperature controlled using electrical heating elements with the exception of the last one, where torrefied material was cooled using a water jacket. In order to ensure inert conditions and remove the volatiles, each part of the reactor (including the hopper and the collecting container) was purged with a nitrogen flow of about 8 NL/min.

Feeder and screws were driven by individual motors allowing for basically independent setting of mass flow (feeder setting) and residence time (screw setting). However, since the filling degree of the screws was limited, the settings were not fully independent from each other.

2.3. Fluidized bed gasifier

Gasification experiments were conducted on a laboratory-scale pressurized fluidized bed reactor (PID Eng & Tech, Spain), schematized in Fig. 1. The experimental rig was equipped with a

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