



# Combustion properties of torrefied biomass obtained from flue gas-enhanced reactor



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## ABSTRACT

Torrefaction is the process of thermal treatment that leads to enhanced biomass properties. Specifically, torrefaction of raw biomass can lead to higher energy density, improvement of handling and grinding properties, and other advantages. This work investigates the combustion properties of torrefied biomass obtained from the torrefaction of willow (*Salix viminalis*) in the presence of flue gas. The properties were compared with other solid fossil fuels such as Polish hard coal and Polish lignite. The comparison was based on proximate and ultimate analyses as well as the combustion of the fuels using an auto-thermal bubbling fluidized bed reactor. The combustion process of torrefied willow was stable, and the most promising result was radically low SO<sub>2</sub> emission levels. However, the relatively high NO<sub>x</sub> emission should be decreased by the application of primary or secondary methods of NO<sub>x</sub> removal.

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## 1. Introduction

Sustainable use of biomass fuels in stationary combustion chambers is recognized as an environmental friendly energy conversion process [1,2]. However, the use of raw biomass poses several challenges, including high moisture content, biological instability that results in rotting and mold growth, difficulties in mechanical processes such as pulverization, low energy density [3] and spontaneous emission of gases (e.g. volatile hydrocarbons from biological processes of wood during its storage) [1]. Fortunately, these problems can be readily addressed by torrefaction or carbonization processes. Torrefaction is the process of low-temperature pyrolysis (i.e. thermal conversion without oxidants) carried out in a temperature range of 200–300 °C and a residence time of 15–30 min [4]. It deserves to be mentioned that torrefaction improves the biomass fuel quality by increasing the heating value, destroying fibrous structures, and making the surface hydrophobic [5]. Moreover, torrefaction upgrades materials and it can be stored for a long time. Torrefaction reduces the costs of biomass transportation and storage [6]. From the practical point of view, grindability (kWh/t) of wood chips and wood pellets was reduced almost ten times (achieving value of 23–78 kWh/t) when these fuels were processed by torrefaction. It improved significantly milling process

before co-combustion of coal and biomass in pulverised fuel boilers [7]. Recently, applications of torrefaction in the presence of oxygen have been underscored due to potential applications of flue gas as a torrefaction agent [8–14]. Impact of O<sub>2</sub> [8–12] and CO<sub>2</sub> [13,14] on torrefied biomass parameters was discussed. An overall conclusion was that O<sub>2</sub> and CO<sub>2</sub> presence (up to certain concentration typical for flue gas composition) did not have a negative effect. An efficient torrefaction by flue gas as a torrefaction agent is possible. Table 1 shows the comparison of the investigation conditions regarding to oxygenated torrefaction.

However, studies related to the investigation of torrefied fuel combustion processes in larger scale chambers have not been widely reported in the literature [16,17]. To the best of our knowledge, only a few studies have investigated torrefied fuels in large-scale experimental settings. Ndibe et al. [16] investigated the co-combustion of torrefied spruce and bituminous coal (El Cerrejon coal from Colombia) using a 500 kW<sub>t</sub> pulverized combustion chamber. The authors noticed a significant reduction of SO<sub>2</sub> emissions (from 710 to 124 mg/m<sup>3</sup> STP at 6% O<sub>2</sub>) when torrefied spruce and El Cerrejon coal were co-fired as a 50% mixture. This effect was partially explained by the limited amount of sulfur in the fuel mixture and SO<sub>2</sub> retention in ash. A significant reduction of NO<sub>x</sub> was observed during the monocombustion of torrefied spruce (160 mg/m<sup>3</sup> STP at 6% O<sub>2</sub>) compared to coal combustion (558 mg/m<sup>3</sup> STP at 6% O<sub>2</sub>). This observation was explained by significant differences in N-fuel content (N = 0.2 mass % for torrefied spruce and N = 1.64 mass % for coal). Pimchui et al. [17] investigated the

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**Table 1**  
Comparison of main process parameters during oxygenated torrefaction.

Type of biomass	Conditions, O <sub>2</sub> or CO <sub>2</sub> range, v.%	Type of reactor	Ref.
Impact of O <sub>2</sub> Sugarcane bagasse	0–10% O <sub>2</sub> , 250–310 °C, 45 min.	Vertical stainless steel (AISI 316) tube; diameter of 56 mm and a length of 360 mm.	[8]
Palm kernel shell (PKS)	0–15% O <sub>2</sub> , 220–300 °C, 30 min.	Vertical stainless steel tubular reactor; internal diameter of 0.028 m	[9]
Eucalyptus grandis wood	2–21% O <sub>2</sub> , 240–280 °C, 60 min.	Batch reactor	[10]
Sawdust	0–21% (TGA) and 0–6% (BFB) O <sub>2</sub> , 10 h (TGA), 4–42 min (BFB)	TGA and batch fluidized bed reactor (1.5 m tall and 50 mm in diameter)	[11]
Oil palm fiber and eucalyptus	N <sub>2</sub> or air, 250–350 °C, 1 h	Batch reactor (cylindrical chamber, diameter of 125 mm and height of 440 mm)	[15]
Oil palm empty fruit bunches	0%–15% O <sub>2</sub> , 220–300 °C, 30 min	Horizontal tubular reactor made of stainless steel (internal diameter of 46 mm)	[12]
Impact of CO <sub>2</sub> Bamboo	100% CO <sub>2</sub> , 240–340 °C, 30 min	Horizontal tubular reactor	[14]
Woody biomass (Juniper and Mesquite)	100% CO <sub>2</sub> or 100% N <sub>2</sub> , 200–300 °C, 1 h	TGA and batch torrefaction in the laboratory oven	[13]
This work Willow	0–8% O <sub>2</sub> , ~350 °C, 20 min.	fixed bed reactor, flue gas as a torrefaction agent	This work

combustion of torrefied rice husks in a spout-fluid bed combustor. However, only the temperature distribution of the different combustor zones was studied and discussed.

This paper shows the laboratory study of the willow torrefaction process on combustion conditions within Bubbling Fluidized Bed. Emission levels of gaseous pollutants were analysed and compared with those resulting from the combustion of fossil fuels such as Polish hard coal and Polish lignite.

## 2. Experimental section

### 2.1. Fuel delivery and analysis

Torrefied willow was obtained by thermal treatment of raw willow using a flue gas-enhanced reactor. Torrefaction was carried out in the presence of flue gas from biomass combustion. Raw willow samples (average size of 1–3 mm) were placed in the heated zone of the reactor where warm flue gas was introduced. The average temperature in the reactor and residence time of biomass were approximately 300 °C and 20 min. Detailed information

regarding the torrefaction reactor will be presented at a later time due to ongoing patent procedures. All fuel analyses (proximate, ultimate, combustion heating values) were carried out according to the procedures of Institute for Chemical Processing of Coal (IChPW). The comparison of differences between IChPW procedures and the International/European Standards are presented in Table 2. More particular comparison of these standards were presented by Lasek et al. [18]. It should be explained, according to our experience, that the differences in the values of fuel properties analysed by IChPW procedures and the International/European Standards did not exceed 2% of measured value. Elemental analysis was performed on a LECO TrueSpec (LECO, USA) CHN and a LECO SC 632 (LECO, USA). Combustion heating value was measured using a LECO AC500 (LECO, USA).

### 2.2. Combustion test

Experiments were carried out using a laboratory-scale fluidized bed combustor as described previously [19]. The main component of the experimental setup was a fluidized bed combustor (bubbling

**Table 2**  
Differences between IChPW procedures and the International/European Standards, according to Lasek et al. [18].

Method of analysis	IChPW procedures	International/European Standards
Sample preparation to analysis	Sample granulation: <0.425 mm	Sample granulation: <1.00 mm, <0.25 mm
Moisture content (as received state)	Sample granulation: <60 mm Sample mass: 50 g	Sample granulation: <31.5 mm Sample mass: 300 g (200 g for fine particles, e.g. sawdust)
Moisture content (air-dry state)	Sample mass: ~2 g	Sample mass: min. 1 g
Ash content	Temperature: 600 °C (815 °C for bone meal) Sample mass: 3–5 g.	Temperature: 550 °C Sample mass: min. 1 g.
Sulphur content (total)	Method: combustion in pipe integrated with infra red (IR) absorption, temperature of 1350 °C	Method: ion chromatography, ICP, turbidimetric, IR (after validation)
Higher heating value (HHV)	Sample granulation: <0.425 mm Sample mass: –0.8–1.5 g for traditional calorimeters, –0.25–1.0 g for automatic calorimeters Sample type: loose form or pellet Correction for HHV calculation: including heat released during combustion of wire, thread, tissue-paper and heat released during conversion and dissolution of sulphuric acid in water	Sample granulation: <1.0 mm or 0.5 mm, 0.25 mm, to ensure proper repeatability and complete combustion Sample mass: min. 1 g Sample type: pellet or loose form closed in bag or capsule for combustion Correction for HHV calculation: including heat released during combustion of wire, thread, tissue-paper and heat released during conversion and dissolution of sulphuric and nitric acids in water
Hydrogen content (H)	Temperature: ≥950 °C Sample mass: 30–400 mg	Temperature: according to recommendation of analyzer producer Sample mass: according to recommendation of analyzer producer
Carbon, nitrogen (C, N)	Consistent	

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