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The qualification of torrefied wooden biomass and agricultural wastes products for gasification processes

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ABSTRACT

The present work is focused on the characterization of torrefied biomass and their application for (fast) gasification purposes. Since the upscaling of the torrefaction process from laboratory scale to commercially pilot plants is not fully understood, laboratory results do not reflect the characteristics of commercially available torrefied products gained from theses plants.

A step toward bridging this gap lies in a general evaluation of commercially available torrefied products, which should be independent from the preceding processing conditions and which focuses on the specific requirements of the product's technical application.

In this spirit, this work focuses on different torrefied products and torrefaction degrees examined with selected, common characterization methods. The influence of the torrefaction process on surface characteristics, especially the development of the porous structure, is investigated. The torrefied material is evaluated in terms of its process temperature management via combined thermogravimetric and differential scanning calorimetric analysis. Since empiric predictions based on fossil coals do not match the characteristics of torrefied material, common analytical methods for fossil coals like ultimate and proximate analysis are also discussed.

The methodology laid out in this work enables the user to establish a pre-selection of the torrefied biomass type and the torrefaction temperature for its further application in industrial fast gasification processes.

1. Introduction

To increase sustainability huge carbon-based industries like chemical industry, power industry or steel industry, investigations are carried out to substitute carbon from fossil origins like oil or coal by biomass. In general, the biomass is transformed into gaseous products via different elevated temperature routes. The major route is gasification or combustion under high temperatures in an oxidative atmosphere [1–4].

For combustion purposes the burnout rate of each particle must be close to the maximum, so the residual ash contains no carbon at best. In combustion processes, temperature and oxygen concentration of the atmosphere leads to high efficiency of the carbon containing fuel.

For gasification purposes the oxygen concentration in the atmosphere is reduced, which leads to lower burnout rates than for combustion. A fast gasification requires fast reaction kinetics and therefore demands a careful preparation of the carbon containing fuel [5].

Raw biomass contains large amounts of water, which has to be removed to increase the specific heating values. One of the most popular biomass substitutes, if raw biomass cannot be used, is charcoal. But the solid yield of charcoal after production is only around 33% of the original dry, wooden biomass. The torrefaction process, a mild pyrolysis at lower temperatures, results in solid yield of over 70%, which might be of interest for a sustainable use of biomass [6–9].

Due to the massive weight loss of biomass at temperatures up to 350 °C, the production of torrefied biomass with defined characteristics for gasification like specific caloric values, concentration of carbon in solid residue is difficult to achieve [10,11]. Furthermore, no universal criteria for biomass prepared for gasification is existing, but some proposals have been given to evaluate the

Abbreviations: BET method, Brunauer–Emmett–Teller method; DSC, differential scanning calorimetry; LOM, light optical microscopy; MIP, mercury intrusion porosimetry; PCI, pulverized coal for combustion; TBM, torrefied biomass; TGA, thermogravimetric analysis.

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torrefaction degree [12]. For fossil coals, the amount of volatile matter and fixed carbon in combination with the specific heating values allows a general conception of the gasification abilities of each coal type [13–15]. These values do not match the product characteristics of torrefied materials. An evaluation of torrefied products for fast gasification purposes is not possible, yet. Experimental results from laboratory scale vary from those gained from pilot plants. The torrefaction process itself varies according to the utilized reactor type and further complicating matters. Right now, commercially available torrefied material cannot be evaluated for industrial application.

In this investigation the characteristics of different types of torrefied biomass, especially at high torrefaction temperatures around 300 °C, are presented and evaluated. The torrefaction reactor is a pilot plant (laboratory torbed reactor); its product similar to commercially available torrefied material. Since the torrefaction process defines product quality of its solid residues and therefore its gasification characteristics, a characterization of the torrefied material in comparison to fossil coals is crucial for its further technical application in fast gasification processes.

2. The torrefaction process

The torrefaction process is a mild pyrolysis process at temperatures 200–350 °C. The raw biomass is heated to evaporate the moisture at the initial stage. It loses physically bonded water during the second stage and is heated up to 200 °C slowly. Then the main torrefaction process starts with low heating rates around 10 K/min and the release of volatiles until the torrefaction temperature is reached. After torrefaction time, the product is quenched in order to conserve the solid yield. Due to the post-combustion of volatiles, released during torrefaction process, the process can be run and therefore defined as autotherm.

During the torrefaction process molecular bonded water is released (in combination with carbon dioxide). In contradiction to charcoal the torrefacting biomass does not undergo a molecular reorganization of its structure. Its ignition temperatures in air atmosphere are lower than those of charcoal due to the faster reaction kinetics of the original molecular structure. The specific heating values of the solid products are higher than of raw biomass due to the loss of water during torrefaction process [16].

The torrefied product must be characterized independently from its former torrefaction process to exclude both scaling effects and influences of different reactor types. As mentioned before, common criteria for fossil coals do not match the product characteristics of torrefied materials. Therefore this paper aims to present some characterization methods and its information concerning the general applicability of torrefied biomass for fast gasification purposes.

3. Materials

Two different wood types which are common in European countries were chosen:

- Softwood: Pine wood.
- Hardwood: Beech wood.

The wood samples were, without bark and already chipped, torrefied at three different maximum temperatures to get samples from all temperature levels of the torrefaction process:

- Low: around 220 °C.
- Medium: around 250 °C.
- High: around 300 °C.

Since the interest in biomass has increased during the last years, the prices for wood increased as well. So, three different agricultural wastes were chosen to compare the influence of the torrefaction process on wooden biomass and agricultural wastes. According to the results from the two wood types only high torrefaction temperatures are suitable for fast gasification purposes as the results will point out.

There is a broad variety among agricultural wastes. For gasification purposes this investigation concentrates on hard agricultural wastes like shells.

- Palm kernel shells
- Pine kernel shells
- Almond shells

All biomasses were torrefied under the same process conditions (heating rate and torrefaction time) in a laboratory torbed reactor [17,18]. Proper preparation of the raw material concerning water content, particle size and geometry is crucial for a proper heat transfer inside the reactor for a homogeneous torrefied product. The same is valid for the torrefaction process itself: The heating rate and the torrefaction time must be followed in a small range due to the fast reaction kinetics especially at high torrefaction temperatures. In the case of almond shells, they have been crushed, the other two types of shells were transported through the reactor in whole size. The torrefied products were crushed and milled. It must be stated, that the results of the elementary and proximate analysis depend strongly on the reactor type and its conditions and cannot be simulated by upscaling from laboratory results due to different heat transfer conditions. Recently Aziz et al. have presented their laboratory results on palm kernel shells in [19]. The pilot plant experiments were carried out at the GWI in Essen in cooperation with RWE Innogy. The task at the department of ferrous metallurgy was to evaluate the torrefied product for application in ironmaking processes.

Therefore, in comparison to the results of the ultimate and proximate analysis of the torrefied materials, two additional materials were investigated:

- A commercially available Softwood** (type not specified), heat pre-treatment in absence of oxygen at temperatures between 340 and 400 °C.
- A commercially available charcoal (from beech wood), pyrolyzed between 500 and 600 °C.

**: Material provided by Münch Edelstahl GmbH, Hilden, Germany.

4. Methods

The residual samples according to Table 1 were analyzed using light microscopy analysis, ultimate and proximate analysis after

Table 1
Investigated torrefied samples from different types of biomass.

Biomass	Sample No.	Temperature level		
		Low	Medium	High
Pine wood	1	×	×	×
Beech wood	2	×	×	×
Palm kernel shells	3	–	×	×
Pine kernel shells	4	–	–	×
Almond shells	5	–	–	×