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# Entrained flow gasification of torrefied wood residues

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ABSTRACT

In this work, four different fuels were gasified in a pressurized entrained flow pilot plant gasifier at approximately 270 $kW_{th}$. The different fuels were; two torrefied wood residues, one raw wood residue and one torrefied stem wood. The system pressure and oxygen equivalence ratio ($\lambda$) were held constant for all four gasification experiments. It was found that the torrefaction pretreatment significantly reduced the milling energy consumption for fuel size reduction, which in turn contributed to increased gasification plant efficiency. Furthermore, the results indicate that the carbon conversion efficiency may be enhanced by an intermediate torrefaction pretreatment, whereas both less severe torrefaction and more severe torrefaction resulted in reduced carbon conversions. The results also indicate that the $CH_4$ yield was significantly reduced for the most severely torrefied fuel.

## 1. Introduction

Large-scale, pressurized entrained flow gasification (PEFG) of fossil coal has proven industrially preferable in terms of cost-efficiently producing a clean product gas, essentially free from products of incomplete gasification such as char, soot, tars and other lower molecular weight hydrocarbons (e.g. $CH_4$, $C_2H_2$) [1]. This high conversion efficiency as well as the inherent fuel flexibility are two major advantages of the PEFG-process. There are enough coal based installations around the world, 96 (2010), demonstrating the economic viability of the PEFG process [2]. Global coal based installations are consequently continuously increasing with the majority of the present PEFG projects generally aimed for either power production, petrochemicals or liquid fuel production in China and in the US [2].

A number of studies have also identified PEFG as one of the most promising technologies for large-scale biomass conversion to higher-value energy carriers, liquid fuels and petrochemicals, e.g. [3–5]. Quite few practical PEFG test campaigns have however so far been performed for biomass raw materials at pilot- or commercial scale. Pilot scale PEFG experiments with solid biomass are to our knowledge limited to the studies performed by Weiland et.al, where gasification of stem wood and bark mixtures were gasified at approximately 200 kW scale [6,7]. In addition to this, Wolters et al. and Padban described occasional trials of co-firing coal and biomass in a 250 $MW_e$ IGCC plant in Buggenum [8,9]. In the study of Padban, torrefied biomass corresponded to approximately 70% of the fuel mixture on energy basis. One reason for this limited experience is that biomass powder is generally considered difficult and problematic in terms of feeding [10,11] and ash behavior [5,12].

Compared to fossil coal powder, the use of powder from traditional biomass materials may result in increased tar formation and methane production due to lower flame temperature primarily because of the lower heating value of the biomass. Furthermore, production of powder from traditional biomass often needs expensive equipment adoptions or reconstruction of existing coal handling and powder production equipment. Some kind of biomass pretreatment would therefore be desirable to facilitate the use of commercially available, lower cost and proven handling equipment either in the coal PEFG-train with no or minor adaptations, or in new biomass based installations.

Torrefaction has been identified as such a (promising) thermal pretreatment method to potentially facilitate large-scale cost-efficient PEFG of biomass. By exposing the biomass to temperatures in the region of 230–350 °C during 1 to 60 min, a number of critical material properties are significantly improved to the benefit of subsequent conversion [13]. During the process, biomass is degraded and volatiles are released as torrefaction gas, decreasing the oxygen content and increasing the carbon content of the biomass material. These changes also improve the heating value and friability (i.e. also powder size distribution after

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milling) of the biomass material, and thus potentially influencing both gasification process chemistry and the efficiencies of the process. Furthermore, the fuel particles may become more spherical, making it more easily to feed in pneumatic systems.

Because of the generally improved characteristics of torrefied and compacted biomass materials, the whole supply chain of raw material handling, storage and transportation is significantly improved; costs and carbon footprints are reduced as exemplified by for example Uslu et al. and Svanberg et al. [14,15]. Comparing different pretreatment methods and supply systems for biomass feeding of large-scale PEFG plants it has been concluded that a feedstock based on torrefied materials to be the preferable route for introducing biomass to PEFG systems already developed and available for coal [3,16,17]. Another important aspect in favor for biomass pretreatment by torrefaction is the significant variations in market conditions and thereby economy of a large-scale gasification plant as a result of varying feedstock, $CO_2$ credit and electricity prices. Meerman et al. stressed the importance of flexible feedstock operation, i.e. industrial systems facilitating straightforward switching between coal and torrefied biomass, depending on varying economic and raw material prerequisites [18–20]. A green coal in the form of torrefied biomass materials would facilitate this flexibility since the existing coal feeding system can be used for the torrefied materials while traditional biomass requires a dedicated fuel feeding system [19].

The changes imposed on the biomass during torrefaction may however also result in reduced performance in the PEFG process as volatile matter is decreased and reactivity changed. The process chemistry and behavior of the fuel particles are significantly influenced by the volatile content, particle size distribution and morphology, where the reduced volatile content could decrease reactivity but the smaller particle sizes instead increase the conversion rate during gasification. It should however be stated that the higher reactivity of biomass may in fact allow less requirements on size reduction than what is experienced with coal and also facilitating sufficiently high gasification efficiency at a somewhat lower temperature.

In the work by Couhert et al. [21], atmospheric steam gasification of beech wood and torrefied beech wood was studied in a lab-scale drop-tube furnace at 1200 °C and 1400 °C. It was found that the amounts of residual carbon (char that was not gasified by steam) were higher for the torrefied wood fuels compared to the original beech wood at 1200 °C. This indicates a reduction in fuel conversion efficiency for the torrefied fuels by gasification with steam. However, Chen et al. [22] found that the torrefaction temperature affected the cold gas efficiency (CGE) of their experiments with sawdust performed at 1200 °C in a drop-tube furnace using $O_2$ as the gasification agent. They found an optimum in CGE (i.e. also fuel conversion) at a torrefaction temperature of approximately 250 °C, whereas both less severe torrefaction and more severe torrefaction pretreatments resulted in lower CGE. This result was attributed to the measured pore structure of the fuels, where the sawdust torrefied at 250 °C had the largest specific area and smallest pore size.

Based on the experimental results from the drop-tube experiments described above [21,22], there is an indication that severely torrefied fuels may result in reduced carbon conversion efficiency from gasification. However, the drop-tube results were both obtained with controlled fuel particle size distributions (by sieving) under *allothermal* conditions at fixed gasification temperatures in lab-scale (<2 kW). In the present work we compare the operation of an *autothermal* pressurized entrained flow pilot-scale gasifier (approximately 270 kW) using a reference wood powder and different torrefied materials. The primary objective was to (1) study the effect of torrefaction on the fuel carbon conversion efficiency and (2) study how the syngas content of $CH_4$ is affected by the torrefaction pretreatment. This is an important factor if the syngas is intended for catalytic conversion to synthetic motor fuels, or chemicals, since the $CH_4$ often is inert through the synthesis plant and therefore only accounts as losses.

The secondary, more general, objectives of the present work was to; (3) evaluate the feasibility of feeding and operating the gasifier on torrefied biomass powder and (4) evaluate if the torrefaction would significantly change gasification plant performance.

## 2. Materials and methods

### 2.1. General description of the pilot plant

The Pressurized Entrained flow Biomass Gasification (PEBG) pilot plant, situated at Energy Technology Centre (ETC) in Piteå, Sweden, was designed to operate in slagging mode with process temperatures ranging between 1200 and 1500 °C. The pilot plant is described in detail by Weiland et al. [6] and therefore only a brief description is given here. A schematic process flow diagram is shown in Fig. 1. The PEBG gasifier consists of a ceramic lined reactor followed by a bubbling 2-level water sprayed quench for syngas cooling and smelt/particle separation. The process temperature inside the reactor is measured by five thermocouples at different locations inside the reactor, placed with the tip coincident with the inner reactor wall. One thermocouple was placed at the top part of the reactor, three thermocouples in the middle part of the reactor equally separated by 120° and one thermocouple in the bottom part of the reactor.

The fuel powders were prepared by milling the considered fuel materials in a hammer mill. After milling, the fuel powders were pneumatically transported to two fuel hoppers in the feeding system located above the reactor in the PEBG plant. The two hoppers are operated alternately in order to sustain the process operating pressure. After pressurization of the fuel hoppers, the fuel was transported by the fuel feeding system and introduced in the top of the reactor. The supplied amount of $O_2$ used in the gasification process was controlled by a mass flow controller (MFC) and introduced in the top of the reactor via an $O_2$ register located concentrically outside the fuel entrance of the burner. Moreover, the $O_2$ concentration in the burner $O_2$ register could be altered by introducing $N_2$ (via a $N_2$ MFC) into the $O_2$ flow. An $O_2$ concentration of approximately 90 mol% was used in the burner $O_2$ register for the campaigns described in this work.

A vertically installed electrical heater was used to heat up the reactor ceramics to approximately 1000 °C prior to process start-up. After removing the electrical heater, the powder burner was installed and the gasification process was started at atmospheric pressure by feeding the fuel powder and $O_2$ to the reactor. Pressurization of the plant was then accomplished by gradually closing the pressure control valve on the syngas outlet until the desired pressure was reached. A general start-up procedure was to operate the gasification process at a high oxygen equivalence ratio ($\lambda$) in order to quickly reach a process temperature above 1200 °C. Here $\lambda$ was defined as the ratio between the supplied $O_2$ and the $O_2$ addition at stoichiometric combustion. After reaching approximately 1200 °C, the process conditions were adjusted according to plan. In the case of process shut down, the reactor was purged with $N_2$ to evacuate all product gases before the process was restarted.

The water sprays in the quench (Fig. 1) cooled the raw syngas and other products from the reactor (i.e. gases, particulates and ash/char) to temperatures below 100 °C. Separated particles in the quench (i.e. ash or possible char and soot particles) either settled at the bottom of the quench or in the sedimentation vessel downstream the quench water outlet. The process pressure was controlled by a pressure control valve on the syngas outlet pipe (see Fig. 1). A slip stream of the pressure relieved and cool syngas could be sampled from the outlet syngas pipe. The produced syngas flow was flared on top of the building. A $N_2$ purged and water cooled camera probe was installed in the top of the reactor. The camera was a valuable tool for the operators to qualitatively analyze the gasification flame during operation. For safe process control and automation, a PLC (Programmable Logic Controller) based control system