TORREFACTION FOR ENTRAINED-FLOW GASIFICATION OF BIOMASS

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ABSTRACT: Improvement of grindability and fluidisation properties of biomass through torrefaction is seen as a promising pretreatment option to implement large-scale (entrained-flow) gasification of biomass. The present work aimed for knowledge built-up and generation of design data to support this option. Torrefaction is a thermal treatment of biomass in a temperature range of 200-300 °C. Especially the decomposition of hemicellulose in this range is believed to improve the relevant properties. Compared to untreated biomass, the energy requirements of size reduction can be reduced with 50-85% and capacity expansion of a factor 2 to 6.5 is obtainable after torrefaction. As the fibrous structure of biomass is partly destructed, small particles of 30-400 µm have less needle shape, which improves its fluidisation characteristics. The energy retained in the torrefied wood amounts to 83% to 97% (LHV_daf) and strong property improvements can be achieved at reaction times of less than 10 min.

Keywords: Biomass pre-treatment, gasification, fluidised bed

1 INTRODUCTION

1.1 Problem formulation

Desk studies have identified entrained-flow gasification as a promising option for the large-scale production of syngas from biomass. This biosyngas then is a versatile feedstock for the production of transportation fuels, chemicals and electricity. However, an entrained-flow gasifier requires (sub-)millimetre size feedstock particles. It is difficult and expensive to reduce biomass to this size due to the fibrous structure and the tenacity of many woody biomass.

This led to the idea of applying torrefaction as a biomass pretreatment step. Torrefaction is a thermal treatment at a temperature of 200 to 300 °C, at near atmospheric pressure and in the absence of oxygen. This mild thermal treatment not only destructs the fibrous structure and tenacity of the biomass (wood), but is also known to increase the calorific value and to invert the hydrophilic nature. During the process, the biomass partly devolatilises which leads to a decrease in mass, but the initial energy content of the biomass is mainly preserved in the solid product (fuel). The latter is of great importance to the overall energy efficiency of the biomass-to-biosyngas conversion chain.

Research done on torrefaction has mainly focussed on applications different from the one foreseen in this work [1]. In many cases, research has revealed the influence of torrefaction on the chemical changes of biomass represented by the proximate and ultimate composition, mass- and energy yields, added with some focus on composition of volatile reaction products [2-6]. The positive effects of torrefaction on for instance friability are nearly always mentioned, but have never been quantified in publicly available documentation. Hence, the available knowledge base does not allow a proper techno-economic evaluation of a biosyngas production chain based on entrained-flow gasification with torrefaction as a biomass pretreatment step. The effects of torrefaction on subsequent size reduction and pneumatic feeding should be explored and quantified. Furthermore, these effects should be linked to the mechanisms responsible for the changes in biomass properties to enable a better understanding and optimisation of the torrefaction process.

1.2 Project Objective

The objective of the presented work was to improve the knowledge base on (the mechanisms of) torrefaction and to generate design data with respect to the combination of torrefaction, size reduction and pneumatic
particle feeding. More knowledge was to be gained on the decomposition mechanisms of torrefaction and how these relate to improvements in size reduction and pneumatic feeding of the biomass. The generation of design data concerned the processes of size reduction and pneumatic feeding in relation to the operating conditions during torrefaction.

With respect to the feeding system, pneumatic feeding as applied in existing dry-feed coal-fired entrained-flow gasifiers was taken as a reference. Although it was realised that a 100% biomass-fired entrained-flow gasifier might be equipped with a dedicated feeding system, this was beyond the scope of this study.

1.3 Approach

An extensive experimental programme was conducted on torrefaction, size reduction and fluidisation of (torrefied) biomass. Experiments were carried out using thermo-gravimetric analysis and lab- and bench-scale torrefaction batch reactors (5-10 grams and 3-6 kilograms respectively). In experiments with both batch reactors analysis and sampling of the solid- and the volatile reaction products was performed. Size reduction and fluidisation experiments were done on torrefied biomass that was produced with the 3-6 kg batch reactor. Respectively, a heavy duty cutting mill (1.5 kWe) and a small cold flow fluidised bed (20 x 10 x 3 cm) were deployed. The work was carried out at the Energy Centre of the Netherlands (ECN) and the University of Eindhoven (TU/e) in close collaboration.

2 BIOMASS TORREFACTION

2.1 Important definitions

Two of the most important parameters in evaluating torrefaction are the mass- and energy yield of the process. When looking at the macro composition of biomass, it can be expressed in terms of loosely bound water, organics and ash. The organic part of the biomass contains all the (reactive) chemical energy and during torrefaction part of this energy is removed in the form of reaction products. Therefore, from a fundamental point of view, it is best to express the mass and energy yield on a dry and ash-free basis:

\[
\eta_M = \frac{m_{\text{char}}}{m_{\text{feed}}}_{\text{daf}}
\]

(1)

\[
\eta_E = \eta_M \left( \frac{LHV_{\text{char}}}{LHV_{\text{feed}}}_{\text{daf}} \right)
\]

(2)

In these definitions, use is made of the lower heating value (LHV), although the higher heating value can be used as well. The LHV value of biomass, however, is generally used in the evaluation of many applications and is therefore in a practical sense better understood.

Furthermore, many difficulties in interpreting the torrefaction process arise from the definition of the torrefaction time. The term residence time is frequently used, but it only expresses how long the biomass stays in the torrefaction reactor. Part of the residence time is ‘lost’ due to drying and heating the biomass up to the desired temperature level, and the biomass may be (partly) dried as well during its residence in the torrefaction reactor. Instead, the reaction time is applied, defined as the time that the biomass has a temperature of 200 °C or higher. This includes the heating time from 200 °C up to the desired peak temperature, but excludes the cooling time from this temperature down to 200 °C.

2.2 Torrefaction characteristics

Figure 1 shows the mass yield of torrefied wood in an operating window of 15 – 60 min reaction time and 230 °C to 270 °C torrefaction temperatures. The mass yields range from 78% to 95% and show a gradual decrease with temperature. The observed order of reactivity for the evaluated biomass types is: larch < willow/beech < straw. The differences in reactivity are likely to be related to the differences in hemicellulose content and composition; xylan-containing hardwood is more reactive than mannan-containing softwood (such as larch wood) in this temperature range.

The torrefaction experiments revealed that the process produces a dry, hydrophobic product with an increased energy density. The energy retained in the solid product is in the range of 83% to 97% (LHV$_{\text{daf}}$) and typically 90%. On average, the energy yield also decreases with temperature, but unfortunately this cannot be statistically justified due to a relatively large inaccuracy.
in the determination of heating values (±6%). It is argued that mainly a higher extent of dehydration with increasing temperature explains the interrelation between mass and energy yields. Increasing the torrefaction temperature from 250 to 270°C reduces the required reaction time from 15-30 min to 8-15 min.

![Graph](image)

**Figure 1:** Yield of torrefied wood versus temperature for different biomass types and reaction times; model lines for torrefaction of willow at 15 minutes (upper line) and 60 minutes (lower line) reaction time.

Volatiles formed during the process consist predominantly of (reaction) water, acetic acid, methanol, CO, CO₂, and furan derivatives. The formation varied with the applied conditions where mainly higher temperatures lead to increased formation of these components. The amount and composition of the volatiles are found to be different for hard- and softwood. This can be related to the differences in hemicellulose structure (xylan-, or mannan-based).

2.3 Decomposition mechanisms

The fibrous structure and tenacity (toughness) of woody biomass, but also grasses, is created by nature through a complex structure of mainly three polymeric constituents, viz. cellulose, hemicellulose and lignin. Cellulose fibres are responsible for the fibrous structure and anisotropic properties of (woody) biomass and they are bound together through a matrix of mainly hemicellulose and, to a lesser extent, lignin. Both hemicellulose and lignin are considered to be responsible for the tenacity of the biomass.

In agreement with literature [7], the various experimental work of this project reveals that hemicellulose is the main reactant in torrefaction. Its decomposition can be described by a two-step mechanism of which the first step represents the decomposition of hemicellulose into intermediate partially depolymerised products. The second step comprises charring reactions of the formed intermediates. Modelling of these reactions provided the insight that the first step of decomposition proceeds fast; at higher temperatures (>250 °C) these reactions are completed within minutes. The second step proceeds rather slow having a time frame of hours.

Depolymerisation of cellulose is another important decomposition mechanism. This decomposition mechanism already occurs at low temperature (< 200 °C) and takes an important role in the changes of the biomass structure at torrefaction conditions. At higher temperature, this process takes place faster and to a larger extent. Together with hemicellulose decomposition, cellulose depolymerisation is believed to be responsible for the changes in biomass leading to a decrease of its tenacity and fibrous structure, in respective order.

3 SIZE REDUCTION AND FLUIDISATION OF TORREFIED BIOMASS

3.1 Size reduction improvements

For the size reduction process, the main overall characteristics are power consumption, equipment capacity, and product quality. The first two determine the economics of the size reduction process itself and the last is important for the application of resulting particles as a feedstock for an entrained-flow gasifier.

The results of size reduction experiments using a cutting mill are shown in Figure 2 and Figure 3. It appears that the overall characteristics of size reduction are greatly improved by the application of torrefaction. Torrefaction of wood reduces the power consumption required for size reduction by 50-85%, depending on the applied torrefaction conditions. Simultaneously, Figure 3 shows that the capacity can be increased by a factor of 2 to 6.5. Strikingly, these improvements were
observed for all evaluated biomass (willow, larch, and beech).

Figure 2: Effect of torrefaction on the power consumption of biomass size reduction. Legenda: biomass type (T [°C], reaction time [min])

Further improvement could not be established by increasing the temperature up to 270 °C (at 30 min reaction time). The increase in capacity of size reduction is dependent on the torrefaction conditions in a similar way, but at temperatures higher than 250 °C the capacity of the used cutting mill further increased with the application of a higher torrefaction temperature (at 30 min reaction time). The depolymerisation of cellulose, which proceeds to a high degree with increasing torrefaction temperature, is thought to be responsible for this trend. Shorter fibres are more easily transported through the bottom sieve (classifier) of the cutting mill.

3.2 Pneumatic feeding of torrefied biomass

In dry-feed coal-fired entrained-flow gasifiers, the feeding system comprises a fluidised bed operated in the smooth (non-bubbling) regime by using a pre-defined fluidisation medium. An exit pipe is positioned in the fluidised bed and by applying a pressure drop over this pipe, solids are pneumatically conveyed to the entrained-flow gasifier.

Because of the shortening of the fibres through torrefaction, the particles resulting from the size-reduction process become more spherical (i.e., they have a smaller length-to-diameter ratio), which improves their fluidisation behaviour. Qualitative particle analysis (shape) gave the impression that the length-to-diameter ratio of the particles decreases with increasing temperature. Smooth fluidisation requires an A powder according to the well-known Geldart classification. For torrefied willow, this means that a powder with a size range of approx. 30-400 µm should be produced.

The results from fluidisation experiments are summarised in Table 1. The experiments proved indeed that such a powder (willow torrefied at 270 °C, 30 min reaction time) can be fluidised smoothly, but only in a narrow range of fluidisation velocities. It is believed that further shortening of the cellulose fibres can widen this range. This may be possible through optimisation of the torrefaction conditions (i.e., further increase of temperature in the range of 270 to 300 °C).
Table 1: Qualitative comparison of fluidisation behaviour of (torrefied) biomass and coal. Code: (temperature [°C], reaction time [min])

<table>
<thead>
<tr>
<th>Bed</th>
<th>(d_p) ((\mu m))</th>
<th>Fluidisation Regime</th>
<th>quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>75 -</td>
<td>Smooth</td>
<td>++</td>
</tr>
<tr>
<td>Willow</td>
<td>120</td>
<td>Poor</td>
<td>- - -</td>
</tr>
<tr>
<td>Torrefied Willow</td>
<td>200</td>
<td>Bubbling</td>
<td>-</td>
</tr>
<tr>
<td>(260°C,30 min.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torrefied Willow</td>
<td>160</td>
<td>Bubbling</td>
<td>-</td>
</tr>
<tr>
<td>(270°C,30 min.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torrefied Willow</td>
<td>± 100</td>
<td>Smooth</td>
<td>+</td>
</tr>
<tr>
<td>(270°C,30 min.)</td>
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4 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, applying torrefaction as a biomass pre-treatment process indeed may be expected to contribute largely to the technical and economic feasibility of entrained-flow gasification of biomass using existing (conventional) feeding technology. Prove for this should come from a techno-economic evaluation for which this work provides important input data. Size reduction is enormously enhanced with respect to power consumption (decrease by a factor of 2-6.5) and capacity (increase by a factor of 2-6.5). These results can be obtained for a torrefaction reaction time below 10 min in the higher temperature region explored (250-270 °C). Moreover, particles can be produced that are pneumatically transportable, which is considered impossible for a bed of untreated biomass particles.

The fast decomposition of hemicellulose and the depolymerisation of cellulose are regarded to be the main mechanisms for the observed improvements. The reactivity of hemicellulose mainly contributes to the devolatilisation of biomass and many differences in torrefaction characteristics of various biomasses can be related to this constituent. Further research focusing on torrefaction in the range of 270 – 300 °C is recommended. Operation at such temperatures may allow even shorter reaction times and may further improve the fluidisation properties of torrefied wood.

5 REFERENCES


6 ACKNOWLEDGEMENT

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