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Integrated torrefaction vs. external torrefaction — A thermodynamic analysis for the case of a thermochemical biorefinery

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ABSTRACT

Integrated and external torrefaction is analyzed and compared via thermodynamic modeling. In this paper, integrated torrefaction is defined as torrefaction integrated with entrained flow gasification. External torrefaction is defined as the decentralized production of torrefied wood pellets and centralized conversion of the pellets by entrained flow gasification. First, the syngas production of the two methods was compared. Second, the two methods were compared by considering complete biorefineries with either integrated torrefaction or external torrefaction. The first part of the analysis showed that the biomass to syngas efficiency can be increased from 63% to 86% (LHV-dry) when switching from external torrefaction to integrated torrefaction. The second part of the analysis showed that the total energy efficiency (biomass to methanol + net electricity) could be increased from 53% to 63% when switching from external torrefaction to integrated torrefaction. The costs of this increase in energy efficiency are as follows: 1) more difficult transport, storage and handling of the biomass feedstock (wood chips vs. torrefied wood pellets); 2) reduced plant size; 3) no net electricity production; and 4) a more complex plant design.

1. Introduction

Torrefaction is a low temperature pyrolysis process that can be used as a pretreatment process for biomass. The process can also be referred to as a roasting process and is, e.g., used for roasting coffee beans in the production of coffee. The torrefaction of woody biomass operates typically at 250–300 °C and produces a solid fuel with properties that resemble those of coal. These properties include increased energy density, improved grindability/pulverization, hydrophobic nature, etc. Torrefaction is typically envisioned to be done decentralized, followed by pelletization or briquetting to lower handling, transportation and storage cost. The pretreated biomass can then be sent to a central biomass processing facility [1–3].

Because torrefied biomass has similar properties as coal, it can be gasified using commercial entrained flow coal gasifiers [4,5]. This can enable a relatively quick shift from coal to biomass for syngas production. In Ref. [5], torrefied wood powder is gasified in a 270 kWth oxygen-blown pressurized entrained flow gasifier. The gas produced consist of H_2, CO, CO_2, H_2O and 0.9–1.8 mol% CH_4, together with small amounts of higher hydrocarbons, including tar and soot. A low content of hydrocarbons (~CH_4), and a high content of H_2 and CO, is preferable when using the syngas for chemical synthesis. It is concluded in Ref. [5] that torrefaction reduces the CH_4 content in the syngas, and it is shown that increasing the torrefaction temperature from 300 °C to 340 °C lowers the CH4 content, but at the cost of a lower cold gas efficiency [5]. The disadvantage of entrained flow gasification of torrefied biomass is the relatively low cold gas efficiency achieved due to the high temperature in the gasifier. When also considering the loss of heating value in the torrefaction step the “overall cold gas efficiency” becomes even lower. A method to increase the cold gas efficiency of entrained flow gasification of torrefied biomass has been presented by Mark Prins et al. [4]. The method is about integrating the torrefaction step with the entrained flow gasification. This means that the torrefaction process is done centralized at the gasifier and not decentralized, resulting in higher transportation, handling and storage cost of the untreated biomass compared to torrefied biomass pellets [6].

This paper will compare centralized torrefaction with the more conventional decentralized torrefaction, or when the perspective of a centralized plant is taken; compare external torrefaction to

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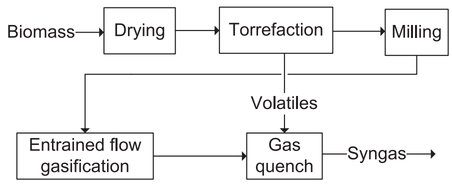

Fig. 1. Simplified flow sheet showing the idea behind integrated torrefaction as presented in Ref. [4]. Note: for case c and d presented in the text: biomass = wood chips (willow).

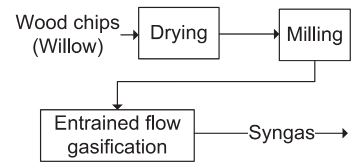

Fig. 2. Simplified flow sheet of syngas production from willow without torrefaction. Note: Untreated willow is assumed to be able to be gasified in an entrained flow gasifier. Moreover, the same gasification conditions as those used for torrefied wood are assumed applicable.

integrated torrefaction. This paper will add to the knowledge that is available in the open literature about integrated torrefaction, by building on top of the analysis performed by Prins et al. in Ref. [4]. This paper will examine the integration between torrefaction and gasification more closely – mainly concerning the increase in the overall cold gas efficiency. Some of the questions answered include: what causes the increase in the overall cold gas efficiency? How do torrefaction conditions influence the increase in overall cold gas efficiency? How does the overall cold gas efficiency compare with external torrefaction or no torrefaction? These questions are answered by thermodynamic modeling of the biomass to syngas conversion (torrefaction + gasification). The integrated torrefaction process will however benefit from heat integration with the downstream syngas conversion processes; such as the conversion of syngas to fuel product, or syngas to electricity. Because of this, the paper will also show the impact of using either external torrefaction or integrated torrefaction in a thermo-chemical biorefinery via thermodynamic modeling and analysis. The impact is assessed by comparing the fuel energy efficiencies as well as the total energy efficiencies along with an assessment of the complexity of the plant designs. Many studies have been published on modeling and analysis of thermo-chemical biorefineries, such as [7–11], but none have used integrated torrefaction.

2. Integrating torrefaction with entrained flow gasification

The concept of integrated torrefaction is presented in Fig. 1. It shows how the volatile gasses produced in the torrefaction process can be converted to syngas when using entrained flow gasification [4].

In decentralized torrefaction, the volatile gasses are typically combusted to produce heat for drying and torrefaction [2]. In a centralized plant, the use of medium and low temperature waste heat for drying and torrefaction is more optimal, and the volatile gases can then be used to chemically quench the high temperature gas from the gasifier and thereby increase the production of syngas.[1] The method was proposed by Mark Prins et al. in Ref. [4]. Mark Prins et al. write that "due to the high temperature, the thermally unstable volatiles from the torrefaction step will decompose into carbon monoxide and hydrogen" [4]. This claim is the core of the integrated torrefaction process and is therefore also a prerequisite for this paper. It should be noted that the claim still needs to be verified by experiments. If future experiments show that the volatiles are not decomposed into hydrogen and carbon monoxide to a very significant extent, the method would probably not be attractive, especially if significant amounts of tar compounds in the volatiles from torrefaction "survive" the high temperature quench. If this shows to be the case, a dedicated downstream tar reforming/cleaning process, similar to what is used when gasification is done in fluidized beds, would be required. A dedicated downstream tar reforming/cleaning process would normally not be needed after an entrained flow gasifier [5,12].[2]

To evaluate the integrated torrefaction process, a parameter called the "overall cold gas efficiency" is defined as follows:

$$\text{overall cold gas efficiency} = \frac{\dot{m}_{\text{syngas}} \cdot \text{LHV}_{\text{syngas}}}{\dot{m}_{\text{biomass,dry}} \cdot \text{LHV}_{\text{biomass,dry}}} \quad (1)$$

This parameter is the total energy efficiency for the integrated system, which consists of torrefaction and gasification (and gas quench).

In Section 2.2, the values for the overall cold gas efficiency are presented for four cases. The cases are a) without torrefaction (Fig. 2), b) external torrefaction (Fig. 3), c) integrated torrefaction at 250 °C (Fig. 1) and d) integrated torrefaction at 300 °C (Fig. 1). The modeling approach used to generate the results for the four cases is presented in Section 2.1.

2.1. Modeling of torrefaction and gasification

Torrefaction is modeled in a certain way for the case of external torrefaction and in another way for the cases of integrated torrefaction. For external torrefaction, simply using the energy efficiency of torrefaction is adequate (Eq. (2)), but for integrated torrefaction, torrefaction is modeled in more detail based on two torrefaction experiments presented in Ref. [4].

$$\text{energy efficiency of torrefaction} = \frac{\dot{m}_{\text{torr\_wood}} \cdot \text{LHV}_{\text{torr\_wood}}}{\dot{m}_{\text{biomass,dry}} \cdot \text{LHV}_{\text{biomass,dry}}} \quad (2)$$

The two experiments are summarized in Fig. 4. The two experiments estimate the reaction heat for torrefaction to be lower than 1% of the LHV of the wood input, but the estimation is associated with an uncertainty of 2.2%–2.5% of the LHV of the wood input. The two experiments also show that only 1% of the heating value in the wood input is lost in the torrefaction process (converted to sensible heat).

For external torrefaction, the energy efficiency of torrefaction is set to 80% (dry LHV) irrespective of the torrefaction temperature. This setting agrees with a review on torrefaction [1] and with data on the production of torrefied wood pellets [14,15].[3] An energy efficiency of torrefaction of 80% also matches the torrefaction

[1] When pressurized entrained flow gasification is used, the volatiles must be pressurized before the gas quench (Fig. 1). This pressurization can either be done by 1) pressurizing the volatiles after torrefaction, 2) pressurized torrefaction, 3) a combination of options 1 and 2.

[2] This is true for coal gasification [5,13], and experiments performed in Refs. [5,12] with wood and torrefied wood indicate the same.

[3] The torrefaction energy efficiency is close to 80% for external torrefaction irrespective of the torrefaction temperature because of the heat requirement for drying. The heat requirement for drying is independent of the torrefaction temperature and much higher than the heat requirement for torrefaction. In many references, torrefaction efficiencies higher than 80% are stated, e.g., Refs. [14,15]. The efficiencies in these references are based on LHV on wet basis instead of dry basis. This difference can clearly be seen in table 2.2 in Ref. [15] and figures 4.4 and 4.5 in Ref. [14]. One of the consequences of basing the energy efficiency on LHV wet basis is that the process of drying wood will produce heating value, even though chemical reactions do not take place.