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Research paper

Detailed mapping of the mass and energy balance of a continuous biomass torrefaction plant

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ABSTRACT

Biomass torrefaction was tested on pilot scale (50 kg h^{-1} throughput) for 3 types of wood: spruce, ash and willow at torrefaction temperatures of 250 °C–265 °C. Quantitative analysis of process streams was accomplished by utilising on- and off-line analytical methods.

The data obtained from the pilot tests could be very well translated into large-scale operations. A theoretical overall thermal efficiency of 88–89% was calculated for a large-scale heat-integrated torrefaction process that uses wet woody feedstock containing a mass fraction of 45% moisture.

These results show that a pilot plant is most suitable not only for exploration of (new) feedstocks but also for generating experimental data that provide valuable information for the design of full-scale plants. The detailed mapping of the mass and energy balances presented in this work can be used further as input for process optimisation, evaluation of commercial viability and techno-economic analyses which can further help in up-scaling and commercialisation of the torrefaction technology.

1. Introduction

In all future energy scenarios, biomass and bioenergy play a major role in the transition to a sustainable society and to a circular economy [1]. In these energy schemes, a renewable form of carbon is necessary for the production of solid, liquid and gaseous fuels as well as materials and chemicals. Biomass is the only sustainable feedstock containing carbon that has the potential to be converted into these valuable products.

The types of biomass feedstocks to be utilised preferably in advanced generation of bio-products are residues and wastes, fast-growing grasses and wood species as well as mixtures of these and, generally, all renewable organic feedstocks that do not interfere with the food chain on any level. These type of feedstocks are often tenacious and fibrous, bulky, non-homogeneous, high in water content, biodegradable and, generally, prone to issues in storage, handling, transportation and processing.

In order to overcome these issues, torrefaction can be applied as a biomass pre-treatment process. Torrefaction is a thermochemical process that, together with a proper densification, can produce a high-quality solid bioenergy carrier, which can serve as a renewable alternative to coal, e.g. in coal-fired power plants [2,3]. Torrefaction in combination with densification transforms the biomass into a more coal-like product which has a higher energy density, is more hydrophobic and is easier to grind than the initial raw biomass [4,5].

Torrefaction is a thermochemical pre-treatment process typically in the temperature range of 200–300 °C. The chemistry behind torrefaction involves mainly the removal of oxygen from the biomass structure after exposure to a hot, oxygen-deficient atmosphere [5–7]. During torrefaction, besides the desired torrefied solid product, also by-products are formed, namely gases, condensable organics and water, which are all contained in the torrefaction gas. Torrefaction gas can be combusted to generate process heat. The torrefied product can be further processed and densified into pellets or briquettes obtaining a solid bioenergy carrier with a high energy density, better adjusted to logistics and end-use requirements [8]. The overall process scheme of the torrefaction concept is presented in Fig. 1. In a large-scale optimised torrefaction scheme, the torrefaction gas can be combusted, if needed together with part of the feedstock (e.g. bark, fines, etc.). This can provide the necessary heat for the torrefaction reactions to proceed but also for pre-drying the feedstock to reduce the initial moisture content.

During torrefaction, mainly the hemicelluloses in the biomass devolatilise as is also illustrated in Fig. 2 by means of thermogravimetric analysis of wood and its constituents [9]. Xylan is one of

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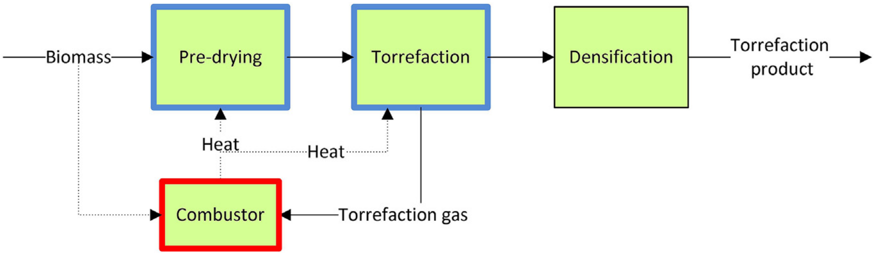

Fig. 1. Overall torrefaction process scheme. Blue units require heat and the red unit releases heat. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

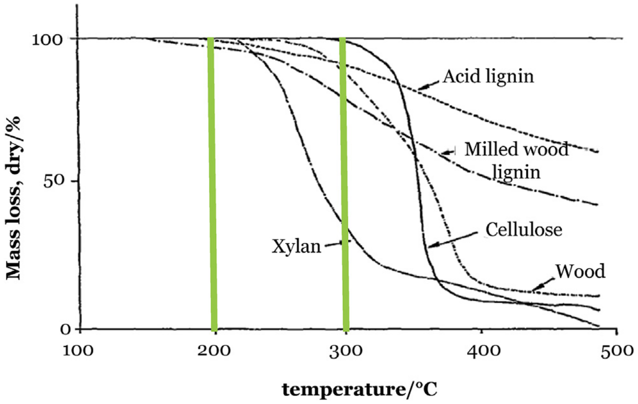

Fig. 2. Devolatilisation pattern of cotton wood and wood constituents. Green lines indicate torrefaction temperature regime. Linear heating rate: 15 K min^{-1}. Adapted from Ref. [9]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the components of hemicellulose. Decomposition, devolatilisation and depolymerisation are the three major reactions that take place during torrefaction [10]. These reactions are initiated at temperatures around 200 °C [9,11].

Table 1 summarises the composition of the types of lignocellulosic biomass also used in this present research. Deciduous wood is also known as hardwood and it contains more hemicellulose and less lignin than coniferous wood (softwood). Hemicelluloses are highly temperature sensitive and the extent of wood decomposition also depends on their amount and composition. A xylan-based hemicellulose (present in hardwoods) is more temperature sensitive (i.e., easier to decompose) than a mannan-based hemicellulose (present in softwoods) [12].

Publications on the topic of torrefaction have increased drastically in the past decade which indicates the interest on this subject and the significance of the steps forward that are being taken by scientists. Most of the research on torrefaction concerns the modelling of torrefaction reaction kinetics and mechanisms [13] as well as process modelling [14,15] and reactor modelling [16]. However, the amount of experimental data that is available on pilot scale torrefaction in continuous reactors appears to be limited. The literature includes results obtained from continuous rotating drum reactors [17–19], an auger screw type reactor [21] and a new torrefaction technology termed REVE (Vibrating Electrical Elevator and Reactor) [22].

Table 1
Lignocellulose composition of deciduous and coniferous biomass types [20].

Polymer, mass fraction/%	Deciduous	Coniferous
Lignin	18–25	25–35
Cellulose	40–44	40–44
Hemicellulose	15–35	20–32
Composition Hemicellulose, mass fraction/%		
4-0 methyl glucuronoxylan	80–90	5–15
4-0 methyl glucuronoarabinocyxylan	<1	15–30
Glucomannan	1–5	60–70
Galactoglucomannan	<1	1–5
Arabinogalactan	<1	15–30
Other galactose polysaccharides	<1	<1
Pectin	1–5	1–5

Batidzirai et al. [23] modelled mass and energy balances based on experimental data obtained from an existing torrefaction plant. Torrefaction experiments were performed with eucalyptus and straw as feedstocks. However, no experimental data could be provided due to confidentiality reasons. A study by Karlsson [19] used results of 345 kg h^{-1} to 364 kg h^{-1} (rotating drum) torrefaction trials with a wood residue mixture to perform mass and energy balances. Lemus and Gil [21] presented results of their 500 kg h^{-1} pilot plant which they use to determine mass and energy balances, as well as process efficiencies of an integrated torrefaction process based on cereal straw as feedstock. Doassans-Carrère et al. [22] also used results of torrefaction of wood chips on pilot scale (40 kg h^{-1} and 80 kg h^{-1} throughput) to perform a brief techno-economic analysis.

Most of the data available in the literature was generated using small-scale lab equipment and has been further used by researchers to asses torrefaction process performance. Syu and Chiueh [24] used experimental data from the literature on torrefaction of rice straw for their process simulations. They developed an energy and mass flow model which they used for evaluation of system performance. Chen et al. [25] did an energy analysis of the torrefaction of micro-alga residues using data obtained from their lab-scale experimental set-up. They introduced an index of relative energy efficiency (REE) to evaluate the energy utilisation performance in such a torrefaction system. Granados et al. [26] performed thermogravimetric analyses (TGA) on a variety of feedstocks (sugarcane bagasse, banana rachis, rice husk, palm oil fibre, sawdust and coffee waste). These data were used to perform an energy and exergy analysis in order to calculate the respective efficiencies. Van der Stelt in his thesis [27] uses experimental results obtained from his lab-scale torrefaction experiments with beech wood to perform mass and energy balances in an attempt to calculate the heat of reaction.

The aim of this work is to aid to the expansion of publically available experimental data on continuous pilot torrefaction processes. Additionally, we demonstrate how process flows of a pilot plant can be quantified by using on- and off-line analytical methods. The detailed mapping of the mass and energy balances presented in this work are of great significance for process optimisation, evaluation of commercial viability and techno-economic analyses which can further help in up-scaling and commercialisation of the torrefaction technology.

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