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Torrefaction of beechwood: A parametric study including heat of reaction and grindability

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HIGHLIGHTS

- ▶ Beechwood chips are torrefied at lab scale with different parameters.
- ▶ Mass loss of the dry solid is a good indicator for the degree of torrefaction.
- ▶ Heat consumption of the reactor is measured to determine the heat of reaction.
- ▶ The heat of reaction ranges from −199 J/g (exothermic) to 148 J/g (endothermic).
- ▶ Grindability in terms of HGI is moderate or easy for solid mass loss >30%.

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ABSTRACT

Torrefaction describes a thermal treatment of biomass in order to obtain a solid product with more or less coal-like properties. Therefore a mild pyrolysis in an oxygen-free atmosphere is applied. In this work beechwood was used as feedstock because of its consistent quality in commercially available chips. A parametric study was conducted with a continuously working, indirectly heated reactor having a throughput on the order of 1 $kg_{product}$/h, wherein each parameter was varied independently. The reactor temperature ranged from 270 to 300 °C, residence time from 20 to 60 min, and feed moisture content from 0% to 20%. Ultimate and proximate analysis of the products as well as grindability tests have been performed. Additionally, the integral heat of reaction was determined for each test run by measurement of the heat consumption of the reactor. Mass loss of the dry solid is shown to be a good indicator of the degree of torrefaction and ultimate as well as proximate analysis show good agreement with existing literature data. Grindability in terms of HGI depends on the degree of torrefaction and reaches from difficult to grind to very easy to grind. In terms of beater wheel mills used for combined drying and milling in lignite fired power plants, grindability is poor and in general worse than that of Rhenish lignite. The heat of reaction is found to be close to the border between endo- and exothermic with a trend to more exothermic behaviour for increasing degree of torrefaction. Despite the uncertainty of the heat capacity of wood and torrefied wood above a temperature of 420 K, the determined heat of reaction is found to be in the range of −199 J/g (exothermic) to 148 J/g (endothermic) for all tests with spans of about ±70 J/g for each single test run. Besides severe torrefaction, caused by a high reactor temperature, an increased residence time is found to cause a remarkable exothermic heat of reaction.

1. Introduction

Biomass is a source of renewable energy, which can be converted to heat and power in line with demand. This is an advantage over photovoltaic and wind power making biomass an important pillar in the energy supply today and in the foreseeable future. However, the energetic usage of biomass is challenging, since transport over large distances is often not viable due to its low heating value, the grindability is not sufficient for milling with existing equipment, e.g. in coal-fired power plants and, furthermore, storage is difficult due to micro organisms causing decay. To overcome these challenges torrefaction has been proposed as a process for upgrading biomass by thermal treatment [1–3]. Torrefaction is a kind of mild pyrolysis, typically utilizing temperatures ranging from 200 to 300 °C and residence times in the magnitude of a few minutes to about one hour. To avoid combustion, torrefaction has to take place in the absence of oxygen. Ciolkosz and Wallace [4] published a review paper in 2011

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summarizing most of the available literature about torrefaction. Numerous publications have already addressed the change in chemical composition and model development to predict decomposition rates. Nevertheless, literature dealing with the following two important aspects of torrefaction is quite rare:

1. Grindability in units the consumers need.
2. Energy demand and heat of reaction during torrefaction.

The objective of this work is to give an overview of the influence of torrefaction temperature and residence time on important fuel parameters like chemical composition, heating value and grindability. Additionally, the energy demand of the torrefaction reactor is measured to determine the heat of reaction, which is an important parameter for the control of large scale torrefaction plants.

2. Experimental setup

Beechwood chips without bark have been used as raw material for the torrefaction experiments since they can be purchased with relatively constant quality except for the moisture content. The latter varied between 5% and 15%, hence the feedstock has been dried at 105 °C until the weight kept constant and then remoistened to the desired moisture content. The thickness of these chips is about 2 mm, the particle size determined via sieve analysis is given in Table 1.

Torrefaction experiments were performed with a lab-scale continuously working reactor consisting of a horizontal pipe (length: 1000 mm, diameter: 160 mm) with a screw-conveyor for precise control of the residence time (Fig. 1).

The beechwood chips are fed from a storage container (not shown) to the reactor by a rotary feeder and leave by gravity to a collecting vessel (not shown). To keep the reactor free of oxygen and guide the volatiles to their outlet, flows of technical nitrogen (99.5% purity) are applied to both, the storage container as well as the collecting container. Flow rates are 1 and 0.5 standard litres per minute, respectively. Heating is accomplished indirectly by hot air flowing through the annular gap between the inner and outer pipe in cocurrent flow with the wood chips. Inlet and outlet of this air are shown in the top view in Fig. 1.

Feeder and screw are driven by individual motors allowing for basically independent setting of mass flow (feeder setting) and residence time (screw setting). However, since the filling degree of the screw is limited, the settings are not fully independent from each other (compare Table 2, Test ID 6).

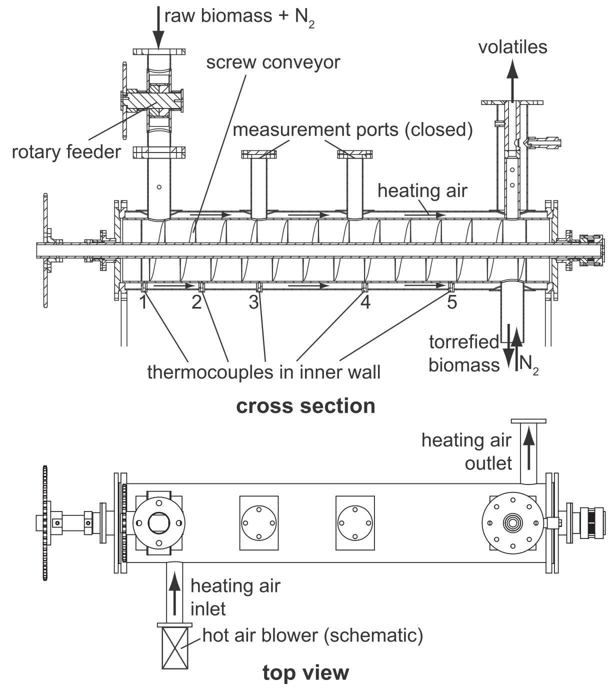

Fig. 1. Sectional view and top view of the utilised torrefaction reactor.

Table 2
Overview of torrefaction parameters of the conducted tests.

Test ID	temperature (°C)[a]	Residence time (min)	Feed moisture (wt.%)	Feeder setting (kg/h)[b]
1	280	40	10	3
2	270	40	10	3
3	290	40	10	3
4	300	40	10	3
5	280	20	10	3
6	280	60	10	2[c]
7	280	40	0	3
8	280	40	20	3
9	300	15	0	8

[a] This temperature is the average of temperatures 2–5 in Fig. 1, compare also Fig. 2.
[b] Since the feeder was calibrated with wood pellets, the real feed mass flow is lower. It is approx. 0.45 multiplied with the stated values.
[c] To avoid jamming of the screw, the mass flow had to be reduced for a residence time of 60 min.

3. Theory and experiments

3.1. Torrefaction

A parameter variation has been conducted to expand the data for torrefaction behaviour of woody biomass. Reproducibility of tests with the utilised reactor is high as has been proven in previous tests [5], hence no repetitions were performed. To keep the number of tests small, a reference has been defined and starting from this, the parameters temperature, residence time and moisture content of the feed have been varied. Since several authors (e.g. Arcate [6], Bergman et al. [1] and Pach et al. [7]) stated 30% mass loss of the dry mass as typical, reference parameters based on preliminary tests were chosen, which (approximately) match this typical mass loss. The chosen reference parameters were a reactor temperature of 280 °C (average of temperatures 2–5, compare Fig. 1), a residence time of 40 min and a feed moisture content of 10 wt.%. An overview of the tests conducted is given in Table 2.

The mean reactor temperature was kept constant at the desired torrefaction temperature by a controller, which sets the electrical heating power and thus the temperature of the (constant) heating air mass flow.

Table 1
Particle size of raw beechwood chips.

Sieve size (mm)[a]	10	8	6.3	5	3.15	2	1	0.63	0.315
Fraction < sieve (wt.%)	1.57	14.4	28.6	48.4	6.87	0.08	0.01	0.02	0.01

[a] Test sieves according to ISO 3310–1 have been used.