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Research paper

Influence of biomass torrefaction parameters on fast pyrolysis products under flame-equivalent conditions

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ABSTRACT

Pretreating raw biomass via torrefaction changes fuel specific properties like grindability, volatile content, energy density and biochemical stability and thus enables an enhanced fuel replacement for pulverized fossil fuel fired furnaces.

In this study, the influence of torrefaction temperature on devolatilization behavior is investigated in a small-scale fluidized bed reactor approximating flame-equivalent conditions. Therefore the pyrolysis products of two different biofuels with varying degree of torrefaction are determined via ex-situ FTIR gas analysis in an N_2 atmosphere in the temperature range from 873 to 1473 K. Furthermore, the mass fraction of residual char particles is determined by adding O_2 to the fluidizing gas and analyzing the burnout products. Char fraction and volatile composition are used to estimate the energy release distribution between homogeneous volatile combustion and heterogeneous char burnout.

The experiments revealed enlarging char yields at the expense of volatile yields with increasing degree of torrfaction at all investigated pyrolysis temperatures. Furthermore, torrefaction favors higher fractions of CO_2 and lower fractions of CO and C_2H_x in the light gas. Further on, no significant impact of torrefaction conditions on the tar composition could be identified. The calculation of higher heating value (HHV) based on char yield and gas composition reveals an overall increase of HHV, while the relative contribution from the volatile fraction decreases with increasing degree of torrefaction. Following this, an increase of torrefaction degree will shift combustion from a high intense volatile combustion in the near burner region towards a less intense but prolonged char conversion in the far burner region.

1. Introduction

The usage of solid biogenic fuels as alternative fuels in coal-fired pulverized fuel boilers can reduce net carbon emissions of power plants [1] and allows for a negative carbon balance when carbon capture and storage (CCS) technologies are applied. The main technical drawbacks in replacing conventional fossil fuels with biomass are the divergent fuel properties of biomass, especially higher volatile content, lower energy density, fibrous structure, lower biostability, and inhomogeneity. A thermal pretreatment via torrefaction helps to improve those properties to generate a more coal-like biogenic fuel [2].

For design and optimization of torrefied biomass-fired furnaces (e.g. Li et al. [3]), detailed knowledge of the pyrolysis/devolatilization product distribution is required to predict ignition behavior, pollutant formation and energy release from volatile combustion in the near-burner region. The pyrolysis product distribution depends on pretreatment parameters (torrefaction temperature, residence time) and on pyrolysis conditions such as temperature, heating rate and residence time.

Table 1 lists experimental studies investigating the influence of different torrefaction conditions on the product distribution during pyrolysis. There is a general consensus in these studies that an increased degree of torrefaction favors the formation of solid char and reduces the amount of released liquid products, either called tar or bio-oil. Regarding the amount of released non-condensable gases, different dependencies on the degree of torrefaction are evident. An overall slight tendency can be identified that lower pyrolysis temperatures favor an increased gas yield with increasing degree of torrefaction, while higher

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Table 1
Literature overview of experimental studies investigating pyrolysis products of biomass samples with varying degree of torrefaction in comparison to the raw material.

Reference	Fuel	Torrefaction conditions		Pyrolysis conditions		Behavior of pyrolysis products with increasing degree of torrefaction[a]								
		Temp. [K]	Time [min]	Temp. [K]	Heating rate	Gas	Tar	Char	H_2O	CO	CO_2	CH_4	H_2	$C_{2+}H_x$
Barontini et al. [4,5]	Palm kernel shell	473–573	30	up to 900	20 K min^{-1}				y↘	y↘	y↘			
				1173	high					c↘	c↷	c↘	c↷	c↘
Boateng et al. [6]	Hardwood, switchgrass	undefined		unknown	high	y↗	y↘	y↘						
Cen et al. [7]	Corn stalk	523	30	773	high	y↘	y↘	y↘		c↘	c↘	c→	c↘	c→
Chen et al. [8–10]	Rice husk, cotton stalk, pine	473–563	30	773	high	y↶	y↘	y↘						
				773	high	y↶	y↘	y↘		c↘	c↘	c↘	c↘	c↶
				823	high	y↘	y↘	y↘		c↘	c↘	c↶	c↘	c↶
Li et al. [11]	Palm kernel shell	473–573	30	1173	$10^4 - 10^5$ K s^{-1}	y↘	y↘		c↶	c↶	c↶	c↶	c↘	
Louwes et al. [12]	ash wood, spruce	523–553	45	773	high					c↘	c↘		c↘	
Raut et al. [13]	Poplar	523–573	60	1073	high	y↘	y↘	y↘						
Ren et al. [14]	Douglas fir sawdust	513–583	8–22	753	unknown	y↘	y↘	y↘		c↘	c↘	c↘	c↷	
Ru et al. [15]	Poplar	473–573	30	up to 1173	10 K min^{-1}			y↘						
Tsalidis et al. [16,17]	Spruce, ash wood	563–573	20–30	773–1273	600 K s^{-1}	y(T)	y(T)	y↘		y(T)	y(T)	y(T)		
				873–1273	600 K s^{-1}	y↘	y↘	y↘		y(T)	y(T)	y(T)	y(T)	
Wafiq et al. [18]	Miscanthus	523	30	1073	800 K s^{-1}	y↘	y→	y↘		y↘	y↘	y↘	y→	y→
Wannapeera et al. [19]	Leucaena Leucocephala	473–593	0–1140	up to 1073	10 K min^{-1}	y↘	y↘	y↘	y↘	y→	y↘	y→		
Xin et al. [20]	Licorice residue	483–553	60	723–1073	2×10^4 K s^{-1}					c↘				
Zhang et al. [21–23]	Rice husk	483–583	30–60	823	high	y↘	y↘	y↘		c↘	c↘	c↘	c↘	c→
Zheng et al. [24–27]	Pine, corncobs, hemicellulose, cellulose, lignin	483–593	10–60	793	high	y↶	y↘	y↘						
				743	high	y→	y↘	y↘						
				873	2×10^4 K s^{-1}	y↘	y↘	y↘						

[a] y: mass yield c: gas concentration ↘: strong increase ↘: slight increase →: constant ↘: slight decrease ↘: strong decrease ↶: maximum ↶: minimum (T): function of pyrolysis temperature.

pyrolysis temperatures favor a decreasing gas yield. Regarding the release behavior of individual gas species, the discrepancies between the different studies are much more pronounced.

To characterize both – the impact of torrefaction and pyrolysis conditions – temperature dependent studies are required, which only have been undertaken by Tsalidis et al. [16,17] and Xin et al. [20]. The lack of experimental data for biomass with a varying degree of torrefaction undergoing pyrolysis processes at high temperatures and high particle heating rates was already identified by Barontini et al. [5] but has not been remedied yet.

The objective of this study is to close the identified gap in the currently available experimental data. To achieve this, the impact of torrefaction temperature on fast pyrolysis yields and gas composition under conditions similar to those in the ignition zone of pulverized fuel boilers is investigated. The yields of 22 single gas species are calculated from an FTIR gas analysis in the exhaust gas stream of a batchwise operating small-scale fluidized bed reactor, which has already been used for several pyrolysis studies [28–30]. Experiments have been undertaken in the temperature range from 873 to 1473 K at high particle heating rates of approximately 5×10^4 K s^{-1} for two different fuels and two different degrees of torrefaction per fuel, to quantify both: the influence of torrefaction and pyrolysis conditions on the gas yields.

The data presented in this study has two main usage scenarios: It can be used to improve the prediction of the higher heating value of pyrolysis products released from torrefied biomass depending on the torrefaction- and pyrolysis conditions. And the data can also serve as a basis for adapting available network pyrolysis models for coal to the pyrolysis process of torrefied biomass.

2. Material and methods

The experimental investigation performed in this study can be divided into three main steps: fuel pretreatment, fuel analysis, and determination of fast pyrolysis products. In the first step, raw biomass is transformed into torrefied biomass under different conditions by using a small-scale continuously working screw reactor. In the second step, the torrefied product is analyzed, ground and sieved into different particle size fractions. And in the third step, one of these fractions is fed batchwise into a small-scale fluidized bed reactor to investigate fast pyrolysis yields under flame-equivalent conditions.

2.1. Raw fuel characterization

In the present study, two different biogenic fuels are investigated. Beech wood (*Fagus sylvatica*) is chosen as a representative for woody biomass and miscanthus (*Miscanthus × giganteus*) as a representative for stalk biomass, respectively. Both biomasses have been cultivated in northern Germany and have been acquired from industrial manufacturers (Beech wood: *Goldspan GmbH & Co. KG*, Miscanthus: *Miscanthus OppStock GbR*). Both materials constitute a mix of plants harvested at different plant ages. Mechanical pretreatment undertaken by the manufacturer resulted in beech wood chips with typical dimensions of 10 × 10 × 2 mm and shredded miscanthus with strongly elongated particles up to 5 cm in length. The material has been stored in sealed plastic bags until use in the laboratory.