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Research article

Atmospheric entrained-flow gasification of biomass and lignite for decentralized applications

Jens Schneider [a], Christian Grube [a], André Herrmann [a], Stefan Rönsch [a,b,*]

[a] Syngas Technologies, Department Biorefineries, Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Torgauer Str. 116, 04347 Leipzig, Germany
[b] Department of Industrial Engineering, Ernst-Abbe-Hochschule Jena, Carl-Zeiss-Promenade 2, 07745 Jena, Germany

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ABSTRACT

The present study deals with the development of a small-scale entrained-flow gasification technology for the decentral use of biomass. Gasification experiments with woody biomass in a wide range of particle diameters d_S in the fractions $0.04 < d_S < 0.11$ mm, $0.20 < d_S < 0.25$ mm, $0.25 < d_S < 0.50$ mm, and $0.50 < d_S < 1.0$ mm were carried out in an atmospheric electrically-heated entrained-flow gasifier at temperatures between 950 and 1100 °C. Power plant lignite in the fraction $0.05 < d_S < 0.08$ mm was gasified as well for comparison. These low temperatures were chosen in order to verify that an entrained-flow gasification technology operating at mild conditions can be developed. Low investment costs combined with the production of a tar-free syngas make this technology option attractive especially for decentralized applications (<5 MW fuel input power). The production of a high syngas quality during autothermal operation has still to be demonstrated.

A short review of studies prepared for entrained-flow gasification of biomass since 2006 points out the state of the art and most important findings. The concentrations of H_2, CO, CO_2 and N_2 together with carbon conversion, cold gas efficiency and syngas yield resulting from the present work are reported and compared to the respective literature values. Carbon conversion, cold gas efficiency, and specific syngas volume varied strongly with temperature and particle diameter showing values between 63 and 100 wt%, 14 and 61%, and 0.6 and 1.4 $m^3\ kg^{-1}$ (STP), respectively. With the present set up, high cold gas efficiencies were only obtained at temperatures of 1100 °C and particle sizes of less than 0.2 mm.

Particle residence times in the gasifier were measured at 25 °C for three sawdust fractions and varied between 1.4 and 3.3 s. These measurements indicate that the particle residence time is not equal to the gas residence time in general. A model for the calculation of particle velocities and residence times at ambient and gasification conditions is presented. The interrelationships between particle residence time, particle diameter, carbon conversion, and temperature are discussed.

1. Introduction

1.1. Background

For the transition of the energy system from fossil to renewable energies, economic, environmental and supply security concerns have to be considered [1,2]. The use of bioenergy technologies provides a possibility to meet these concerns. Bioenergy technologies allow a substantial reduction of net CO_2 emissions [3,4], while providing energy reliably and weather-independent [5], which cannot be guaranteed by wind and solar power plants alone.

Especially the gasification of lignocellulosic biomass is a versatile biomass conversion pathway producing energy-rich gas that can be used for the generation of electrical power [6–8] and basic chemicals [9–14]. However, for a competitive market implementation and use in small-scale bioenergy plants (<5 MW fuel input power), the investment costs of this technology have to be reduced. Especially downstream processes like gas cleaning are complex and related to high specific investments in small-scale facilities. For a reduction of the gas cleaning equipment [15,16] and the related investment costs, the production of a tar-free syngas is a crucial factor.

Entrained-flow gasifiers are able to generate a tar-free syngas that is nearly free of hydrocarbons [17]. They are commercially available e.g. as large scale coal gasifiers typically constructed for a few hundred megawatt fuel input power and operated at extreme pressures (40–80 bar) and temperatures (1400–1600 °C) [17,18]. Commercial entrained-flow gasifiers for biomass are under development.

* Corresponding author at: Syngas Technologies, Department Biorefineries, Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Torgauer Str. 116, 04347 Leipzig, Germany.
E-mail address: Stefan.Roensch@dbfz.de (S. Rönsch).

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1.2. Objective of this work

Comparably low investment costs for a gasifier operating at mild conditions and being constructed of less expensive materials motivate this work. Pressures above 40 bar and temperatures above 1400 °C necessitate not only heavy and durable materials but also intensive safety precautions, which are expensive and seem to exclude the operation of small-scale bioenergy plants. Hence, this work is aimed at investigating an entrained-flow biomass lab-scale gasifier working at comparatively mild operation conditions (atmospheric pressure, temperatures ≤1200 °C) and to prove its applicability for future small-scale facilities (<5 MW fuel input power). Experiments were carried out in order to identify a working point, in which the electrically heated lab-scale gasifier reaches high carbon conversions and cold gas efficiencies.

Nomenclature

Symbol	Description	Unit
η_C	Carbon conversion	wt%
η_{CG}	Cold gas efficiency	%
A	Cross section of tubing	m^2
ρ_G	Density of gas	kg m^{-3}
d_S	Diameter of particles	m
F_d	Drag force	N
C_d	Drag force coefficient	–
μ_G	Dynamic viscosity of gas	Pa s
λ	Equivalence ratio (excess air ratio)	–
τ_{min}	Minimal residence time	s
α	Parameter for drag force coefficient	–
β	Parameter for drag force coefficient	–
p	Pressure	Pa
Re	Slip Reynolds number	–
T	Temperature	K
u	Velocity (particle, gas, slip)	m s^{-1}
$\dot{V}$	Volume flow rate	m^3 h^{-1}

2. Compact review concerning entrained-flow gasification of biomass

Several studies concerning the gasification of various biomasses in entrained-flow reactors were conducted, especially since 2009 [19–42]. The following presentation of research results in Section 2.1 focuses on the influences of the process conditions on gas composition and deduced measures. The conditions studied and major findings are presented chronologically. Entrained-flow gasification technologies that apply biomass and are commercialized or at an advanced development stage are presented in Section 2.2.

2.1. Selected research results since 2006

Zhang et al. conducted gasification experiments with steam and oxygen in nitrogen as well as pyrolysis experiments with N_2 in an entrained drop-tube furnace at temperatures between 600 and 1400 °C [20,26]. Hinoki cypress sawdust with particle diameters below 1 mm was applied at gas residence times between 2 and 4 s. H_2 yields increased with temperature and were high with high H_2O feed (≈39 mol kg^{-1} fuel (dry) at 1400 °C) and low with high O_2 feed (≈12 mol kg^{-1} at 1400 °C) as gasification agent. Dehydrogenation of the fuel's constituents (cellulose, hemicellulose, and lignin) during pyrolysis and of the pyrolysis products (char, tar and hydrocarbons) during gasification led to the formation of H_2. The decomposition of pyrolysis products was promoted at $T > 1000$ °C. CO yields increased from 600 to 800 °C and at $T > 1100$ °C in all atmospheres. At $900 < T < 1100$ °C with H_2O feed, CO yields decreased likely due to the water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$). At $T > 1000$ °C with O_2 and N_2 as well as at $T > 1100$ °C with H_2O as gasification agent, increasing CO yields were explained by the Boudouard reaction ($C + CO_2 \rightarrow 2CO$) and the steam gasification ($C + H_2O \rightarrow CO + H_2$) reaction. CO_2 yields were low with N_2 feed at all temperatures (≤2 mol kg^{-1} fuel (dry)) and increased with temperature with H_2O feed due to the water-gas shift reaction. CO_2 yields were high with O_2 as gasification agent (≈17 mol kg^{-1} fuel (dry)) at $T < 1000$ °C and decreased at higher temperatures.

Furthermore, Zhang et al. [20,26] showed that the concentrations of tars and char decreased with increasing temperature in all atmospheres and resulted in tar yields below 0.8 g kg^{-1} fuel (dry) at a temperature of 1200 °C [26]. Coke (soot) yields increased at temperatures between 800 and 1100 °C and decreased at higher temperatures in all atmospheres. The activities in tar, char, and soot destruction followed the order with respect to gasification agent: $O_2 > H_2O > N_2$. Between 600 and 900 °C, carbon conversion increased with temperature with all atmospheres, decreased up to 1000 °C with H_2O and O_2, decreased up to 1100 °C with N_2, and increased again at higher temperatures. The intermediate decline of the carbon conversion was justified by the competition between hydrocarbon decomposition (forming coke) and carbon consuming reactions with H_2O, O_2 and CO_2 [26].

The effect of steam addition in the gasification of dealcoholized marc of grape (particle diameters below 0.5 mm) with air was studied by Hernández et al. [29]. The effects of the steam-biomass ratio (between 0 and 3.2 mol mol^{-1}) on gas yields as well as of the operation temperature (750 °C ≤ T ≤ 1150 °C) on gas yields in air (between 0 and 2.6 mol air per mol biomass) and air-steam (0 to 100 wt% H_2O) gasification are demonstrated. Major findings of Zhang et al. [26] are supported.

Qin et al. studied the air and air-steam gasification of beech sawdust (median diameter $d_{50} = 280$ μm) and wheat straw ($d_{50} = 170$ μm) at temperatures between 1000 and 1350 °C in an atmospheric electrically-heated entrained-flow reactor [28]. Molar steam-to-carbon ratios varied between 0 and 1, while excess air ratios λ varied between 0.25 and 0.50. Gas residence times between 2 and 3 s were applied. The effects of temperature, steam-to-carbon ratio, excess air ratio and biomass type on gas and soot yields are demonstrated.

The pyrolysis and steam gasification behaviors of beech sawdust in the fractions $0.313 < d_S < 0.400$ mm and $0.730 < d_S < 0.900$ mm were studied by Septien et al. in an atmospheric, electrically-heated drop-tube reactor at temperatures of 1000, 1200, and 1400 °C [33]. Gas residence times varied between 2.2 and 4.4 s. It was shown that soot yields decrease with temperature in a wet atmosphere (75 vol% N_2, 25 vol% H_2O) but increase with temperature in an inert atmosphere (amounting up to 22 wt% of the dry biomass). Tars were present at 1000 °C but completely converted at $T \geq 1200$ °C. Char yields were below 5 wt% at all conditions studied and decreased with temperature in the wet atmosphere due to steam gasification. Consequently, H_2 and CO_2 yields increased with temperature in the wet atmosphere, while C_2H_2, C_2H_4 and C_6H_6 yields decreased with temperature in both inert and wet atmospheres. No significant influence of the particle size on product yields were found at the conditions studied (gas residence times of 2.2 and 4.4 s). It was speculated that particles with diameters of about 1 mm could be gasified effectively in an entrained-flow reactor, which would decrease the pretreatment costs relative to lower diameters.

Yu et al. investigated the gasification of rice straw with particle diameters below 0.3 mm and oxygen-enriched air [38]. The influences of O_2 concentration (up to 60 vol%), equivalence ratio ($0.15 \leq \lambda \leq 0.35$) and gasification temperature ($800 \leq T \leq 1200$ °C) on gas composition, carbon conversion, lower heating value and tar yield are demonstrated. Concentrations of H_2 and CO_2 increase with increasing O_2 concentrations, while CO and CH_4 concentrations decrease. Considering the lower costs for the provision of oxygen-enriched air relative to pure air, $\lambda = 0.25$ and $c_{O2} = 40$ vol% are proposed as reference operation conditions in order to achieve nitrogen-diluted syngas with a lower heating value of 8.2 MJ m^{-3} (STP) and tar yields of 2.6 mg g^{-1}. Yu et al. suggest that membrane technologies could provide oxygen-enriched air with up to 40 vol% O_2 in an economic way [38].