Gasification of biomass-based suspension fuels in an atmospheric entrained flow gasifier

S. Fleck[1], C. Hotz[1], P. Stoesser[1], T. Kolb[1,2]
Karlsruhe Institute of Technology,
[1]Institute for Technical Chemistry, Gasification Technology
[2]Engler-Bunte-Institut, Fuel Technology

Abstract

Experiments on the conversion of biomass based suspension fuels in an atmospheric entrained flow gasifier are reported. Gasification experiments were carried out with glycol as reference fuel and 3 different suspension fuels in order to compare the gasification behavior of the different fuels and to generate a comprehensive data set for process simulation. The solid fuels are pyrolysis char from beechwood and straw as well as biocoal from hydrothermal gasification.

The conversion process is discussed on the basis of local concentration and temperature profiles, supported by SEM and BET analysis of char samples taken from different locations inside the reactor.

1. Introduction

Fossil and biogenic low grade fuels will play an increasingly important role in worldwide supply of power, chemicals and fuels for transportation [1], [2]. Lignocellulosic biomass is a highly heterogeneous energy resource, characterized by a high ash and oxygen content, and low energy density. High pressure entrained flow gasification is an efficient technology for the conversion of a wide spectrum of low grade fuels into a high-quality synthesis gas to be used in subsequent synthesis or power generation processes or in a combination of both (poly-generation). In the bioliq® process developed at KIT, straw and other abundant lignocellulosic agricultural by-products are pre-treated in a fast pyrolysis step. The products (pyrolysis oil and char) are mixed to produce a transportable and pumpable suspension fuel with high energy density, which is then converted to synthesis gas in a high pressure entrained flow gasification process [3].

Present research at KIT and partners is focused on the basic understanding of the thermo-chemical processes during the gasification of a suspension fuel under high pressure entrained flow gasification conditions.

The experiments discussed in this paper are carried out in the atmospheric entrained flow gasifier REGA at KIT using glycol as reference fuel and 3 different suspension fuels in order

to compare the gasification behavior of the different fuels and to generate a comprehensive data set for process simulation.

2. Experimental Set-up

Experimental investigations are carried out at the laboratory Research Entrained Flow Gasifier REGA (see Figure 1) at the Karlsruhe Institute of Technology, KIT. The REGA gasifier is described in detail in [4]. It is operated under atmospheric conditions with a thermal load of 60 kW.
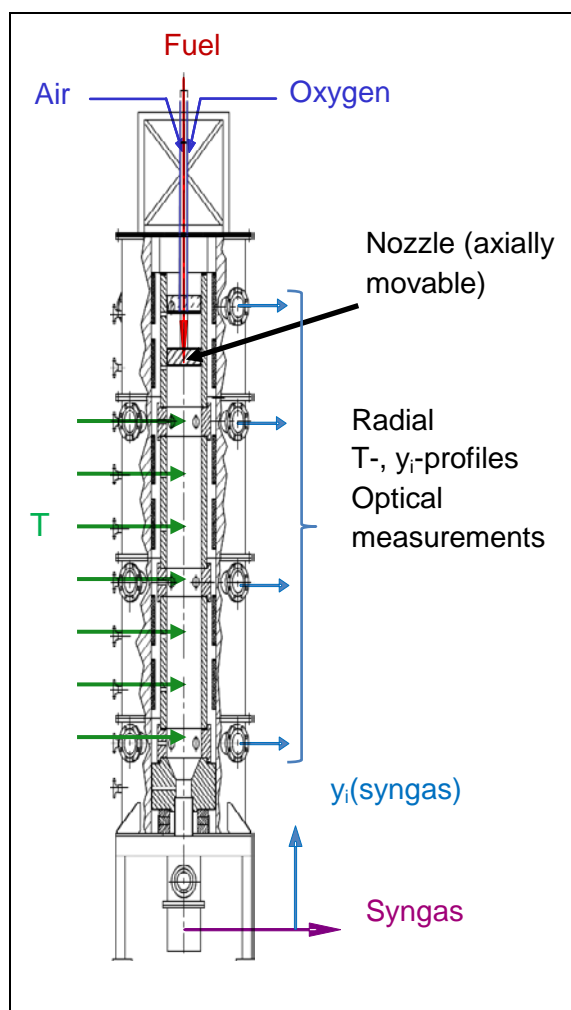

Figure 1: Axial cut through Research Entrained Flow Gasifier REGA.

The reactor provides access for conventional sampling probes as well as for optical measurements through flanges at the circumference and at different heights of the reactor. Due to the vertically movable burner construction, radial temperature and gas species profiles can be measured at variable burner distances [4]. The gas species are determined by ABB standard gas phase analyzers and a µGC, temperature profiles are measured applying double bead type B thermocouples. Particles are sampled at different locations inside the reactor and at the reactor outlet.

The experimental process parameters are defined using an ASPEN Design Spec tool. By applying air with variable oxygen enrichment as atomization and gasification medium, in combination with variable nozzle geometries, an independent variation of stoichiometry, process temperature and spray quality is possible. All measured data are processed by a data evaluation tool in order to assess the data quality.

3. Results and Discussion

Fuel Characterization

For the tests reported here, model fuels with a solid content of 10 wt% were mixed from ethylene glycol and different types of char. Ethylene glycol is chosen as nontoxic liquid model fuel which corresponds in its chemical composition, especially the oxygen content, to typical biomass based pyrolysis oils. Pyrolysis char from beechwood and straw and a biocoal produced by a hydrothermal carbonization process from horse manure and digestate were used as solid fuel components. The beechwood char is a commercial product, the straw char is produced from wheat straw at 500 °C with a solids residence time of 5 min in the STYX pyrolysis reactor at KIT [5], the biocoal is a product of the hydrothermal carbonization process operated by AVA-CO2 in Karlsruhe [6], where the horse manure / digestate feedstock is processed for 2 to 3 hours at 220 °C and 22 bar with a subsequent filtration and drying process.

Table 1 shows the ultimate and proximate analysis for the three solid fuel fractions. The differences originate from the composition of the original biomass and the production processes. The beechwood char has the highest carbon content, whereas the biocoal has the lowest carbon, but the highest oxygen content. For the biocoal the high content of volatiles is remarkable, which lies considerably above the values of the pyrolysis chars. Thus heterogeneous reactions will have a larger influence on solid conversion for the pyrolysis chars as compared to biocoal. The main minerals in the ash are silica, calcium and potassium. Especially the straw char contains high values of potassium, which play influence the reactivity as catalytic active component [7], [8]. In comparison to straw char the amount of catalytic active components is considerably lower for biocoal and beechwood char. The calorific value decreases with the carbon content from beechwood char to biocoal.

Table 1   Composition of the different solid fuel components.

	Beechwood char	Straw char	Biocoal
Ultimate analysis (waf):			
C [wt%]	89.68	85.59	64.51
H [wt%]	3.19	3.92	6.18
N [wt%]	0.67	0.82	1.63
O [wt%]	6.45	9.12	27.43
S [wt%]	-	0.21	0.23
Cl [wt%]	0.016	0.333	0.021
Proximate analysis (ar)			
Moisture	4.7	1.9	9.1
Ash [wt%]	1.6	17.9	10.5
Volatiles [wt%]	20.0	14.6	54.9
C_{fix} [wt%]	73.6	65.6	25.6
Ash composition (wf)			
Si as SiO_2 [wt%]	Not analyzed	10.23	5.21
Ca as CaO [wt%]	0.58	1.55	1.76
K as K_2O [wt%]	0.40	4.11	0.24
Calorific value (wf)			
HCV [MJ/kg]	33.3	27.3	23.4

For the preparation of the gasifier feedstock, the solid fuels were milled and sieved. The median values of the volume size distribution $x_{50,3}$ are given in Table 2.

SEM and BET analysis give additional information on the morphology of the solids (see Figure 4). The beechwood char shows a fluffy highly structured surface. The straw char particles are mainly rod shaped, showing the fibrous structure of the original wheat stems with large pore systems. The biocoal particles show predominately a spherical shape with a smooth surface without visible pores. The specific surface area (BET) of the particles increases from biocoal with 1 m²/g to beechwood char with the highest value of 273 m²/g.

Gasification

Gasification experiments were carried out with glycol as reference fuel and 3 different suspension fuels in order to compare the gasification behavior of the different fuels and to generate a comprehensive data set for process simulation. Table 2 summarizes the operating conditions for the different fuels.

Table 2   Operating conditions.

Fuel	Glycol	GHKS10	GSKS10	GHTCS10
Liquid component	Ethylene glycol			
Solid component		Beechwood char	Straw char	Biocoal
Solid content [wt%]	0	10	10	10
Solids particle size $x_{50,3}$ [µm]	-	4.5	22.3	33.8
Mass flow rate fuel [kg/h]	12.4	11.6	12.5	12.3
Volume flow rate gasification agent [m^3/h]	7.5	8.9	7.7	7.97
Oxygen content gasification agent [%]	69.25	59.03	69.58	65.99
Volume flow rate syngas [m^3/h]	26	26	26	26
Gas to Liquid Ratio	0.83	1.04	0.85	0.89
Stoichiometric ratio	0.47	0.47	0.45	0.47
Adiabatic temperature [°C]	1700			
Mean residence time [s] (at 1200 °C)	3.2			

Figures 2 and 3 show radial profiles of gas species concentration and temperature 300 and 680 mm downstream of the burner tip for glycol and straw char slurry, respectively.
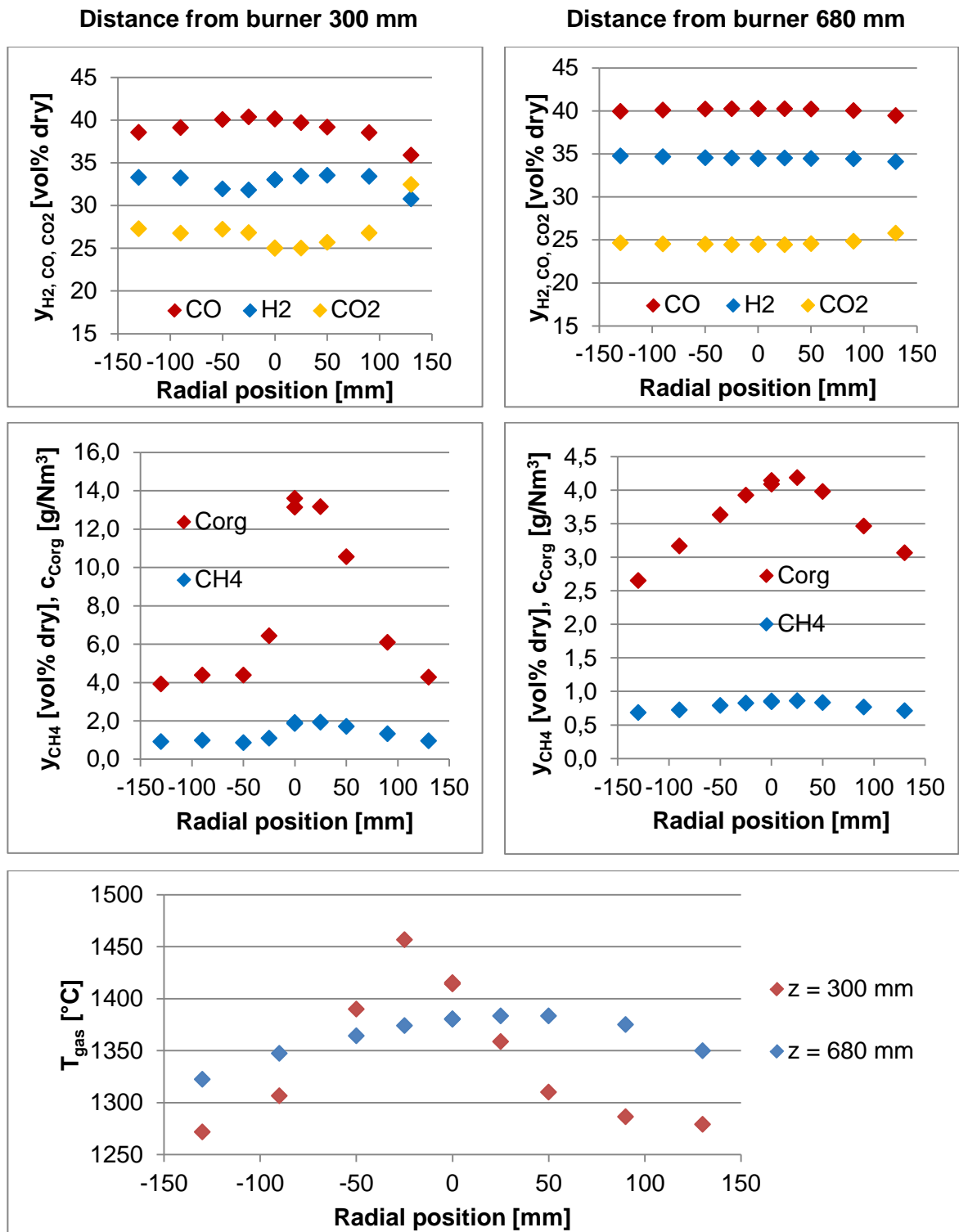
Figure 2   Radial profiles of gas phase composition and temperature for glycol 300 and 680 mm downstream from the burner nozzle.
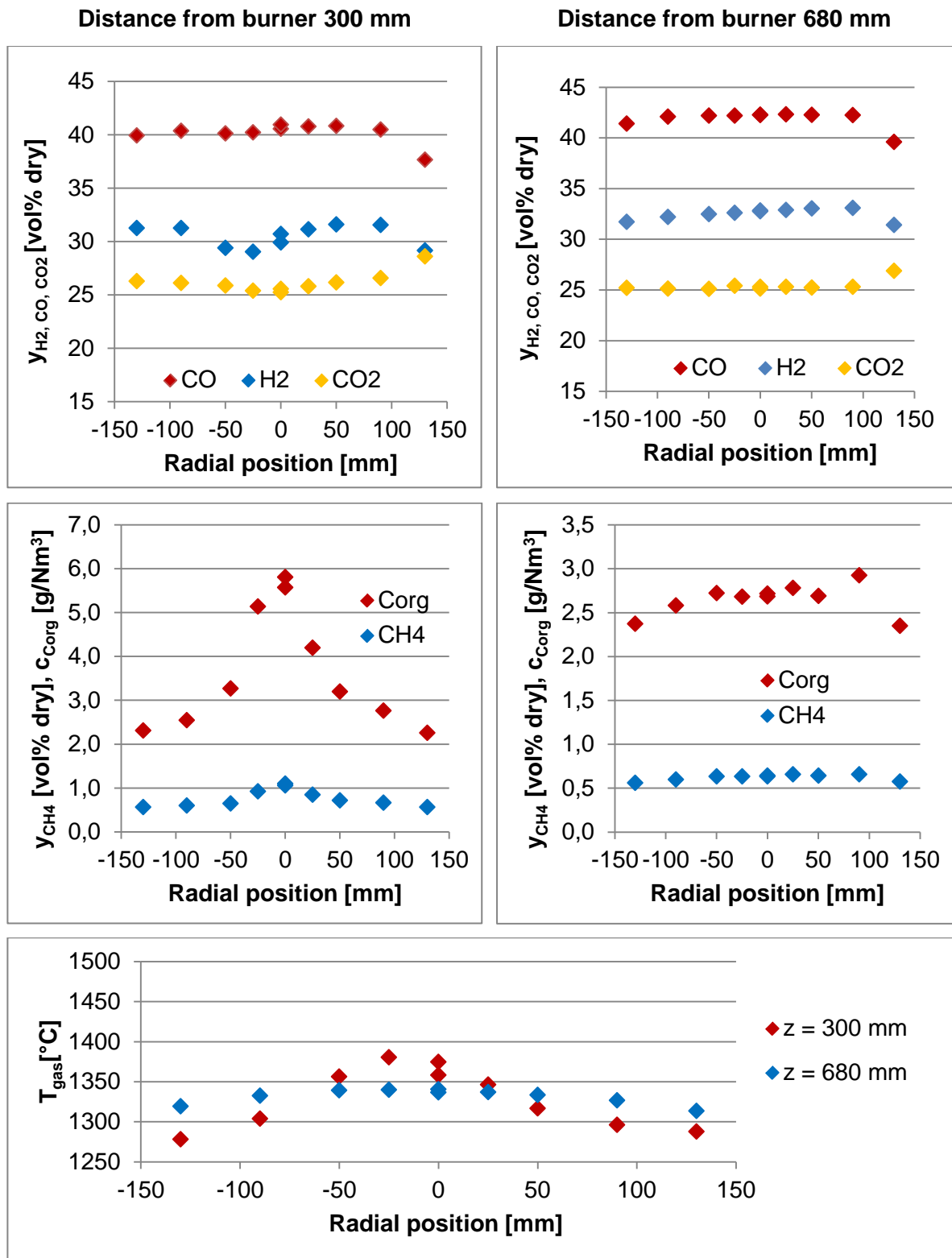
Figure 3   Radial profiles of gas phase composition and temperature for GSKS10 (glycol + straw char) 300 and 680 mm downstream from the burner.

For glycol, the CO, CH_4 and C_{org} profiles show weak maxima on the reactor axis, whereas H_2 and CO_2 concentrations are lower on the axis as compared to the outer recirculation zone. The profiles are most pronounced for CH_4 and C_{org}. The temperature profile has also a maximum on the reactor axis. At 682 mm distance from the nozzle tip the profiles of the main gas components have flattened out, with only marginal changes in absolute value as compared to 300 mm. For temperature and C_{org} a less pronounced radial profile is still detected. CH_4 and C_{org} are reduced significantly in this section of the reactor.

These observations indicate that most of the liquid fuel is converted within the upper 300 mm of the reactor, however large fuel droplets or soot formed in the burner near zone are converted on the reactor axis downstream of 300 mm, without notable contribution to the concentration of the major gas species. The radial profiles of the major gas species and of the gas temperature are flattened between 300 and 682 mm due to intensive mixing.

The profiles for the straw char slurry do not differ significantly from the glycol profiles. The radial profiles at 300 mm are less pronounced. The absolute values differ between the 2 fuels compared, due to slightly different elemental composition of the fuels. The concentrations of CH_4 and C_{org} are lower for the slurry, as compared to glycol. This is also true for the gas temperature which is about 50 K lower for the slurry experiments.

The process efficiency was evaluated by calculating the carbon conversion rate from the gas phase composition measured at the reactor outlet and the measured flow rates. For the unconverted fuel an H/C ratio of 0.8 was assumed. The following table shows the result of this evaluation for the different fuels.

Fuel	C-conversion
Glycol	93.4 %
GHKS10	87.2 %
GSKS10	90.3 %
GHTCS10	92.7 %

Glycol has the highest carbon conversion, followed by the biocoal slurry, straw char slurry and beechwood slurry, with the lowest conversion rate. For glycol, heterogeneous fuel conversion processes do not play a role, except there may be some soot formation in the burner near zone. Biocoal has a very high volatile content, thus, heterogeneous fuel conversion is of minor importance. The high potassium content of the straw slurry acts as catalyst for the heterogeneous fuel conversion process, which results in a better fuel conversion rate as compared to the beechwood char, even though the beechwood char particles are much finer milled as the straw char particles.

Figure 4 shows SEM data from particles in raw condition and taken from the main reaction zone at a distance of 300 (pyrolysis chars) and 680 mm (biocoal) and at the end of the reactor. In addition the BET data for the feedstock is provided.
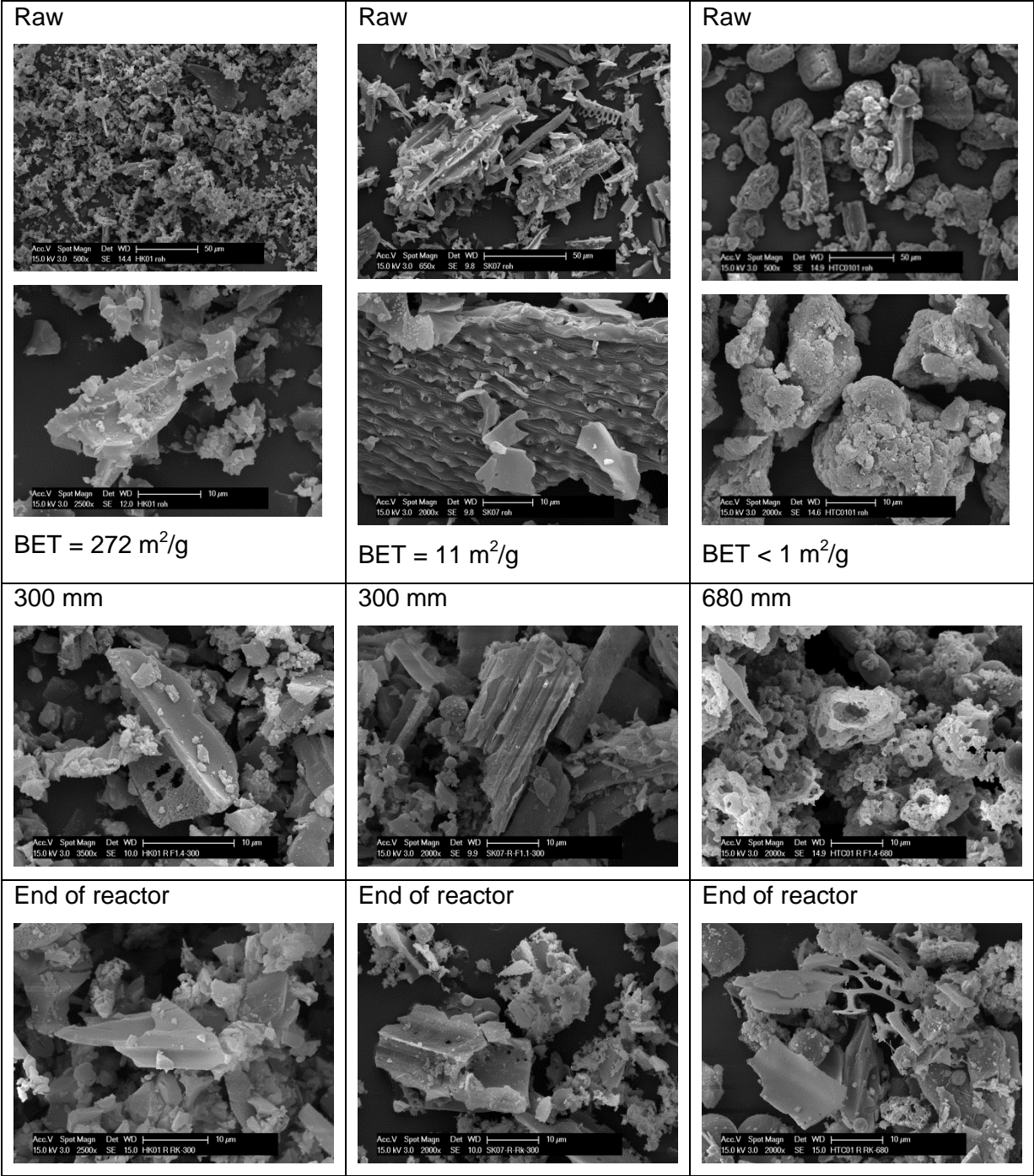

Figure 4   SEM of beechwood char, straw char and biocoal as raw feedstock, taken from the reactor at 300 / 680 mm and at the end of the reactor.

For the pyrolysis chars, the form of the particles seems to remain constant over the whole conversion process. The size of the large pores and channels showing the structure of the biomass seems to be constant as well. Compared to the raw particles in the feedstock the particles taken from the reactor indicate a higher porosity, which is confirmed by first results of BET analysis. For the biocoal the different morphology of raw and reacted particles is significant. Whereas the raw particles have a smooth, closed surface, the particles at the reactor outlet show large pores with similar structures as the pyrolysis char particles. This is not surprising, as the biocoal from a hydrothermal carbonization process is characterized by a very high volatile content, which is condensed tar, on a lignocellulosic carbon structure.

4. Summary

The experiments discussed in this paper are carried out in the atmospheric entrained flow gasifier REGA at KIT using ethylene glycol as reference fuel and 3 different suspension fuels in order to compare the gasification behavior of the different fuels and to generate a comprehensive data set for process simulation. As solid components in the suspension fuels pyrolysis chars from beechwood and straw as well as a biocoal produced via hydrothermal carbonization were used. The fuel compositions as well as the operational parameters are reported.

Radial profiles of gas species concentration CO, CO_2, H_2 and, CH_4, C_{org} and gas temperatures at 300 and 680 mm distance downstream of the burner tip are discussed for glycol and straw char slurry. BET and SEM data of the solid fuel components as raw feedstock material and as char extracted from the gasification process help to explain the experimental results.

There are distinct, axis symmetric radial profiles for gas species and gas temperature at 300 mm distance from the burner tip. The radial profiles of the major gas species and of the gas temperature flatten out between 300 and 680 mm. The radial profiles of the intermediates CH_4 and C_{org} are still pronounced at 680 mm. The profiles for the straw char slurry do not differ significantly from the glycol profiles. From the experimental data it is concluded that the main fuel conversion process is finished within the first 300 mm of the rector for all fuels; however, large fuel droplets and fuel particles on the reactor axis need more residence time and thus maxima in CH_4 and C_{org} concentration are observed due to ongoing fuel conversion on the reactor axis downstream of 300 mm.

For direct comparison of the 4 fuels the process efficiency was evaluated by calculating the carbon conversion rate from the gas phase composition measured at the reactor outlet and

the measured flow rates. Glycol has the highest carbon conversion, followed by the biocoal slurry, straw char slurry and beechwood slurry, with the lowest conversion rate. This descending order is discussed taking into account fuel composition (fixed carbon / volatiles), catalytic ash components (potassium) and particulate structure (particle size / morphology).

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