SMALL SCALE ENTRAINED-FLOW GASIFICATION OF BIOCOALS MADE BY HYDROTHERMAL CARBONIZATION

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ABSTRACT: Recently biomass upgrading technologies like torrefaction and hydrothermal carbonization are investigated to make low quality biomasses and residues available for energetic use. Hydrothermal carbonization offers the conversion of wet, heterogeneous biomass to a homogenous biocoal with enhanced grinding and dewatering properties. In this work the utilization of biocoal in an entrained-flow gasifier is analyzed for subsequent heat and power generation in a gas engine. Basic simulation results of an air-blown gasification process in Aspen Plus® are presented and the development of a small scale autothermal entrained-flow gasifier is described. Large scale technologies like pneumatic dense-phase conveying were applied successfully in small scale with biocoals. Operational experiences and key findings are discussed. First trials were carried out using lignite as comparable fuel.
Keywords: combined heat and power generation (CHP), demonstration, decentralized, gasification, hydrothermal carbonization

1 INTRODUCTION

The utilization of domestic biomasses and residues can provide a substantial contribution to the energy supply market. Recently a focus of interest is on the investigation of technologies like torrefaction or hydrothermal carbonization (HTC) which represent biomass upgrading processes. Thus biomasses and residues which are not energetically used today can be efficiently accessed for thermal processes. In Germany unused biogenic residues offer an energetic potential of 448 PJ mainly from woody and forestry residues as well as from agricultural byproducts [1].

Main restriction to an efficient utilization is the inhomogeneous nature of these feedstocks together with high water contents. HTC as a pre-treatment step produces a homogenous and hydrophobic product with improved grinding characteristics. In this work the application of HTC biocoals for a decentralized entrained-flow gasification process is investigated. For this purpose an industrial like gasifier was designed and put into operation. Combustion engines have special requirements regarding the heating value, particle burden, tars, ammonia and sulfur in the fuel [2-4]. The gasifier design allows measuring these components and values. Furthermore investigations aim at identifying the key parameters in operation mode and fuel pre-treatment in order to produce a gas applicable for a gas engine.

Representing a pre-industrial design the gasifier uses technologies from large scale coal gasifiers allowing a transferability of the results for a commercial plant. The applicability of these technologies and adaptions required for using HTC biocoals are important outcomes of the presented work.

2 HYDROTHERMAL CARBONIZATION

2.1 Technology description

Hydrothermal carbonization is a process of combined dehydration and decarboxylation of fuel in liquid water at elevated temperatures and pressure. Typical operating parameters are 200 °C and pressures of around 20 bar for slightly unsaturated operation. Usually biomass as feedstock is converted within a few hours to a lignite-like fuel after dewatering [5]. Fig. 1 shows a principal concept of a HTC plant with its basic components required to provide a dusty fuel.
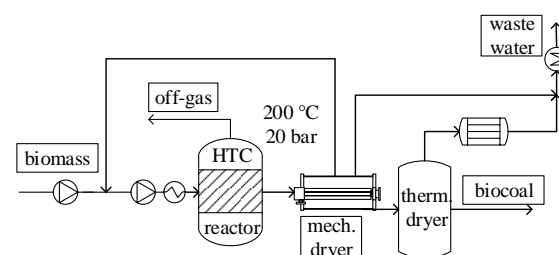

Figure 1: Schematic illustration of a HTC plant for the production of dusty biocoals

2.2 Fuel characteristics of HTC biocoal

During the HTC process the physical structure of the feedstocks is changed. The fibrous nature of biomass is destructed improving mechanical dewatering and grinding characteristics. Atomic ratios of O/C and H/C decrease resulting in elevated heating values. These special properties make HTC biocoals highly applicable for entrained-flow gasification.

Biocoal used within the scope of this project was produced in a demonstration plant at Suncoal Industries GmbH. In Tab. I the chemical analyses of two biocoals are given and compared with Rhenish lignite (RB_BKS). HTC biocoals are made from a biomass mixture (SCI_ETC) and green waste (SCI_GS) at ~200 °C and 20 bar as HTC reaction conditions.

Table I: Ultimate analysis of the different fuels used in this project, %wt (db)

	SCI_ETC	SCI_GS	RB_BKS
C	67,61	61,18	68,26
H	4,13	5,53	5,17
N	0,77	0,71	0,85
S	0,65	0,28	0,92
O	22,72	27,31	20,78
LHV (MJ/kg)	24,81	23,28	24,74

Both chemical composition and heating value are in

the same range for all 3 fuels. Beside that for further processing of the fuels particle sizes distribution plays an important role and is represented in Fig. 2. Biocoal has a larger fraction of small particles but in general a comparable grinding result was possible.
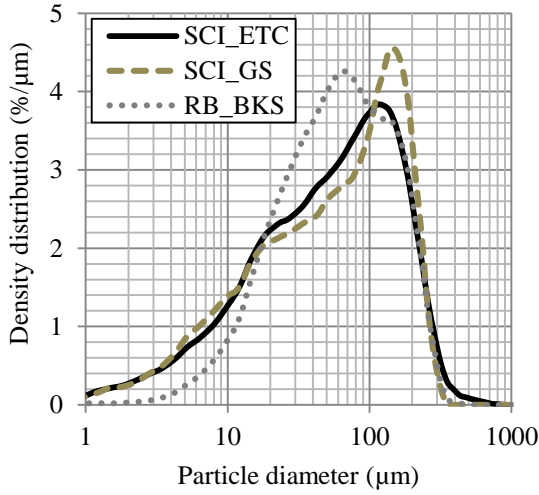

Figure 2: Particle size distribution of the two HTC coals and Rhenish lignite.

3 DEVELOPMENT OF AN ENTRAINED-FLOW GASIFIER

In this project an entrained-flow gasifier was designed and commissioned. The objective was to build an industrial like autothermal process to investigate the applicability of fuels from HTC under realistic conditions. Product gas of the commercial scale-up is intended to be used in a gas engine. Therefor operating parameters of the gasifier are atmospheric pressure and air as gasification agent.

3.1 Basic modeling and evaluation of air-blown entrained-flow gasification

Detailed modeling of entrained-flow gasification is complex and not objective of this work. At this point only some fundamentals are described as a basis for further explanations. Detailed information on advanced modeling is described in [6].

Major restrictions in gasifying with air are due to the low temperatures resulting from the large amount of inert nitrogen that has to be heated up. After pyrolysis the remaining carbon (char) reacts with the surrounding gases. Complete conversion of char is essential for process efficiency. Eq. (1) describes the intrinsic reaction rate of the char after pyrolysis. Neglecting further influences the char reaction depends exponentially on the temperature. Reaction times during entrained-flow operation is in the range of few seconds thus a high char conversion can only be achieved by high temperatures.

$$r_{int} = k_0 \cdot \exp\left[\frac{-E_A}{RT}\right] \cdot p_i^n \qquad (1)$$

Assuming high temperatures the gas composition can be estimated by the water-gas shift reaction, see Eq. (2), being in equilibrium and a balance of the mol streams.

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H < 0 \qquad (2)$$
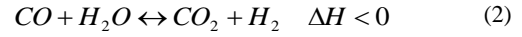
The process efficiency can be determined by the cold gas efficiency (CGE), Eq. (3). It represents the ratio of the energy contained in the syngas to the energy in the fuel input.

$$CGE = \frac{\dot{m}_{Syngas} \cdot LHV_{Syngas}}{\dot{m}_{fuel} \cdot LHV_{fuel}} \qquad (3)$$

3.2 Design parameters of air-blown gasification

The basics given in section 3.1 are applied to an ideal air-blown gasification process assuming complete fuel conversion and neglecting heat losses. Fig. 3 shows the maximum attainable CGE and process outlet temperature for chemical equilibrium depending on the air-fuel equivalence ratio λ. Results are calculated using the simulation tool Aspen Plus®.
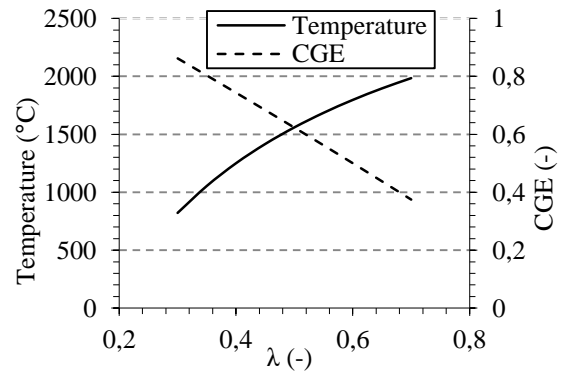

Figure 3: Simulated CGE and equilibrium temperature depending on λ for a gas pre-heating temperature of 500 °C.

For reaching high values of the cold gas efficiency λ should be as low as possible but as already said in practice this would cause a low conversion rate due to low temperatures. A solution for this contradiction is the pre-heating of the gasification agent. Holding the outlet temperature at 1.000 °C, the minimum attainable λ is shown in Fig. 4 by variation of the pre-heating temperature.
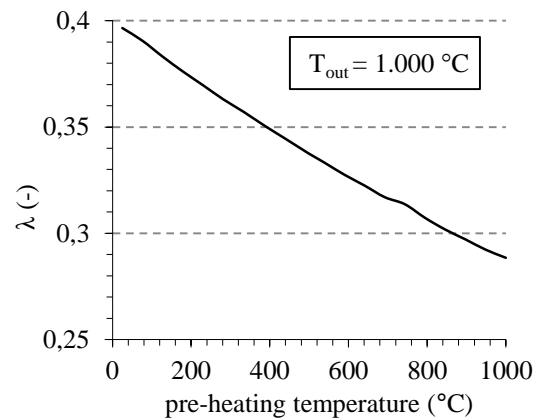

Figure 4: Attainable λ for a fixed outlet temperature as a function of the pre-heating temperature.

3.3 Description of the gasification test rig

The gasifier is designed for a fuel input of 100 kW$_{th}$. It consists of a refractory contained in a water cooled pressure jacket. Electric heaters are imbedded in the refractory for heating up the system before autothermal operation mode starts. Fuel is supplied by a pneumatic dense-phase conveying system thus reducing inert gas dilution of the syngas and assuring a continuous feed.

A schematic representation of the gasifier set-up is given in Fig. 5. Fuel is mixed with pre-heated air in the burner section. A camera is mounted in the top region which allows monitoring of the flame. Hot syngas is water quenched, filtered in a ceramic candle filter and burnt in a flare. Gas and particle probes can be taken and analyzed. Main design parameters of the gasifier are summarized in Tab. II.

Table II: Design parameters of the gasifier

Design parameters	Range
Pressure	0-5 bar
Gasification agent	Air (O_2, H_2O)
Temperatures	1.000-1.500 °C
Gas pre-heating	max. 500 °C
Fuel input	10-25 kg/h
Isolation	Refractory

3.4 Operational experiences

During commissioning and operation some aspects were found indispensable paying attention to. Monitoring of the flame allowed a qualitative statement on the flame stability. This is important because the stability correlates to the gas quality and tar formation. Also occurring break downs of the feeding could be detected online.

The flame stability depends heavily on the feeding system which sometimes has fluctuations in the supply. It could be influenced by adjusting the solid-gas ration and the feed velocity in the conveyor line by fluidization and additional gas.

Fuel is transported to the burner by overpressure in the dosing system. The resulting feeding rate is roughly proportional to the differential pressure. Pressure control of the dosing system and the gasifier therefore must be well adjusted.

HTC coal differs from lignite regarding its feeding characteristics. The dosing system requires good fluidization properties of the fuels. Although particle sizes of tested fuels are comparable SCI_GS needed much higher amounts of fluidization gas and tended to build channels, shafts and bridges in the fluidization zone. A pneumatic periodically moving anchor was installed above the fluidizing bed destroying these disruptions.

4 RESULTS

Fuel feeding system could be operated successfully with different feedstocks. Fuels from Tab. I were all continuously conveyed without rupture for several hours. For reaching this the feeding system was specifically adjusted for each fuel taking into account the different fluidization characteristics.

Gasification trials so far were only performed with lignite. Due to the chemical and physical similarity to HTC biocoals the results are partially transferable. Nevertheless regarding the reactivity of the char and tar formation deviations are expected.
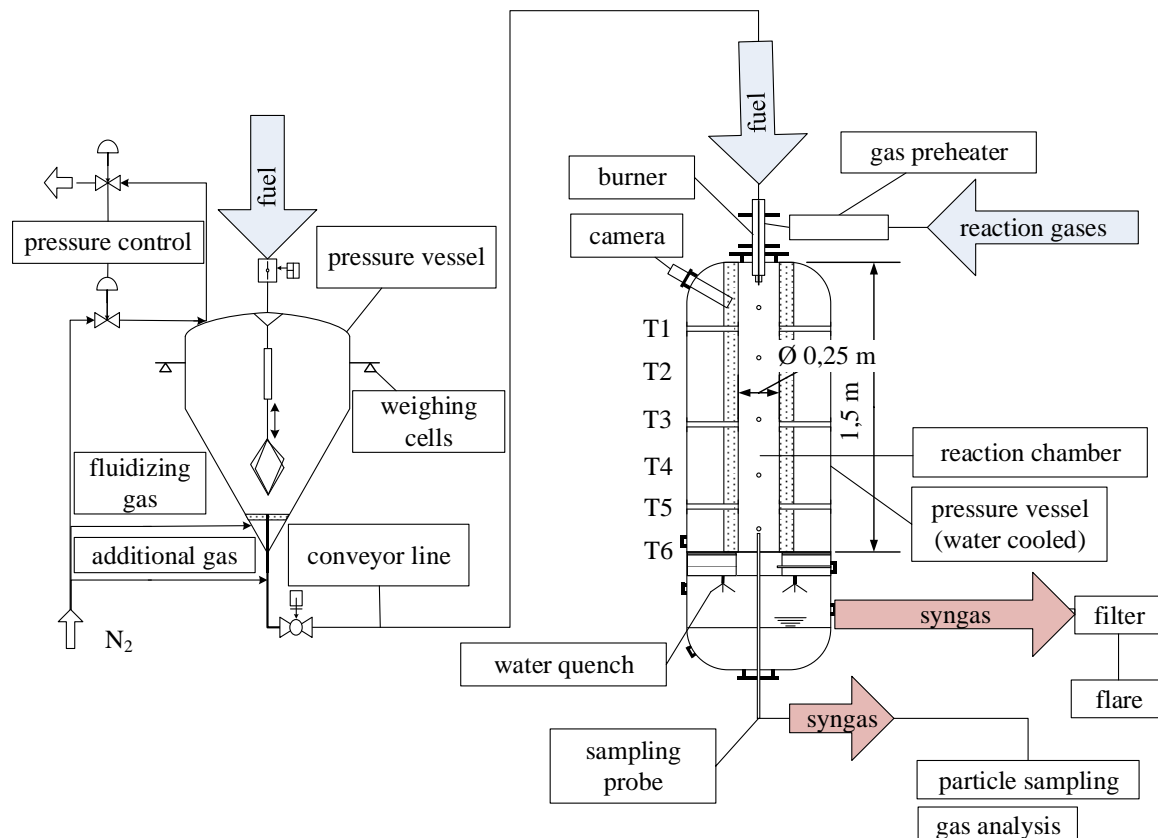

Figure 5: Schematic representation of the gasifier set-up

Fig. 6 shows the axial temperature evolution inside the reaction chamber with time during heating up and at stationary operation with λ = 0,3. Before starting operation the temperatures were electrically raised up to approximately 900 °C. Thereby auto ignition of the fuel-gas mixture occurred making an additional ignition gas burner dispensable. Heating gradient is limited due to thermal inertia of the refractory. A stationary operation is achieved by staged operation varying λ.
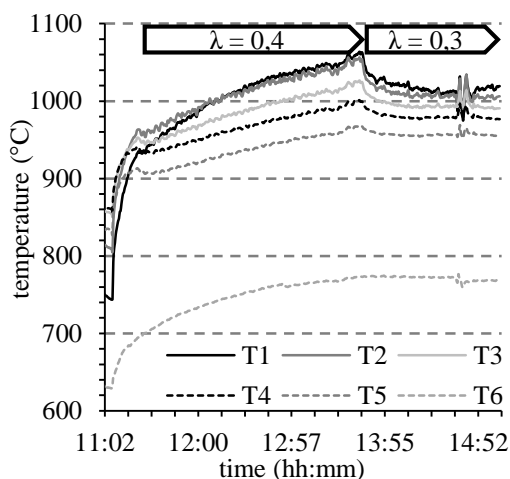

Figure 6: Axial temperature distribution over time during heat up phase and at stationary operation

Gas composition was measured at λ = 0,3 and λ = 0,4 (see Tab. I) at stationary operating points. Hydrogen and carbon monoxide proportion clearly represent the influence of stoichiometry. The notably high content of methane results from low process temperatures and indicates the existence of higher hydrocarbons like tars. These were not measured so far but will be in future. It should be noted that these values do not represent optimized operation but give information about the process efficiency and restrictions.

Table I: Gas composition, vol.-% (water free)

λ	CO	CO_2	CH_4	H_2	N_2
0,4	12,6	12,0	0,9	7,3	67,2
0,3	16,2	10,1	1,3	10,4	62,0

By further analyzing of the gas composition it is possible to draw conclusions on the syngas flow by nitrogen tracer method. Thereby the carbon balance was calculated. CGE is calculated by the heating value of the syngas.

Carbon conversion was 75 % at λ = 0,4 and 66 % at λ = 0,3 respectively meaning that 75 % / 66 % of the carbon from the fuel was contained in the syngas in gaseous form. CGE was 43 % for λ = 0,3 and 40 % for λ = 0,4.

5 CONCLUSION

Hydrothermal carbonization of biomass offers the possibility of upgrading biomasses to a valuable homogenous biocoal. It was shown that biocoal is similar to lignite and thus applicable for entrained-flow gasification due to its good grindability and the hydrophobic character. Further processing of the syngas for energetic utilization should be realized in a gas engine CHP considering that small-scale solutions are already available on the market.

Based on fundamentals of modeling entrained-flow gasification processes a pilot scale gasifier was developed. Operating parameters are atmospheric pressure and air as gasification agent taking into account the simplified handling and reduced investigations for an air separation plant. To reach an adequate efficiency while using air as gasification agent severe pre-heating of the gas is required. Syngas quality then complies the engine requirements regarding heating value and atmospheric pressure.

During commissioning and first trials some key points for successful operation were identified. The feeding systems has a major influence on flame stability and process efficiency. Monitoring the flame is indispensable for process and safety issues. Biocoals have different feeding properties than lignite although chemical and physical properties are apparently similar.

First trials of the gasifier set-up performed with lignite show restrictions in carbon conversion and cold gas efficiency. These are owed to insufficient residence times and unoptimized operating parameters. Additional measurements are required to determine necessary syngas cleaning to match the specifications of gas engines regarding tars, sulfur, ammonia and particles.

6 REFERENCES

[1] Fachagentur Nachwachsende Rohstoffe e.V. (FNR): Biomassepotenziale von Rest- und Abfallstoffen, In: Schriftenreihe Nachwachsende Rohstoffe, Band 36 (2015)

[2] Milne, T.A; Evans, R.J: Biomass Gasifier "Tars": Their Nature, Formation, and Conversion. National Renewable Energy Laboratory, (1998)

[3] Hasler, P.; Nussbaumer, Th.: Gas cleaning for IC engine applications from fixed bed biomass gasification. In: Biomass and Bioenergy 16, (1999), pp. 385–395

[4] Nussbaumer, Th.: Luftreinhaltung und Explosions-schutz bei Holzfeuerungen und Stand der Technik der Holzvergasung. 7. Holzenergie-Symposium. ETH Zürich. Zürich, (2002)

[5] Funke, A.; Ziegler, F.: Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering, In: Biofuels, Bioproducts and Biorefining, Vol. 4 (2010) pp. 160-177.

[6] Tremel. A.: Reaction Kinetics of Solid Fuels during Entrained Flow Gasification, Dissertation, Lehrstuhl für Energiesysteme, TU München, Germany (2012)

9 ACKNOWLEDGEMENTS