

OXYGEN-BLOWN ENTRAINED FLOW GASIFICATION OF BIOMASS - RESULTS FROM A 100 KW TEST RIG

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ABSTRACT: An entrained flow gasification test rig (100 kW, pneumatic fuel feeding 10–25 kg/h) was designed and constructed to be operated either with ambient air at 1000 - 1200 °C or with pure oxygen or an oxygen/steam mixture up to 1500 °C and up to 5 bar_g. In this work first results for the gasification of torrefied wood (mixture) and a raw wood (beech) with pure oxygen are presented. Process parameters are 70 kW thermal firing capacity with an air-to-fuel equivalence ratio λ of 0.4. Applied measurement methods are: online gas analysis, particle sampling (for calculating Carbon Conversion) and SPA (tar analysis)

It turned out that one of the most important points for high conversion and cold gas efficiency is a stable flame. To reach this, the fuel stream from the pneumatic feeding system has to be very continuous. This can be achieved by increasing N₂-input in the conveying pipe. For raw beech wood powder the additional N₂-input has to be higher than for the torrefied wood powder also to avoid plugging. Under the investigated conditions raw beech wood shows better carbon conversion and higher cold gas efficiency. On the other hand the tar concentration is lower and the heating value of the product gas higher for torrefied wood.

Keywords: autothermal gasification, pilot plant, pretreatment, thermochemical conversion, torrefaction, tar

1 INTRODUCTION

An overall goal of the international community is to counteract against the climate change which is mainly caused by CO₂-emissions from burning fossil fuels. For the reduction of these CO₂-emissions it is necessary to produce heat, electrical energy and fuels mostly in a sustainable and renewable way in the future [1]. This is why the use of biomass for energy supply gets more and more important.

In contrast to solid fuels gaseous fuels open the possibility to be used in many different processes to generate electricity and heat (e. g. gas turbine, piston engine, fuel cell) or to produce a secondary energy carrier (e. g. SNG, Fischer-Tropsch fuel). Therefore the conversion of solid biomass to gas is often the first step for the utilization of biomass [2]. All mentioned processes which use the produced syngas for energy supply have requirements regarding the gas quality. Especially the tar content often is a problem. E. g. for combustion engines the maximum permissible value is 100 mg/m³ and for syntheses processes only 0.1 mg/m³ [2].

In the area of thermochemical biomass conversion the state of the art technology is fluidized bed (FB) gasification. Although several commercial plants are operated and the technology is well known it has one main disadvantage: Due to the low operation temperature (< 950 °C) the tar content of the product gas can be high and an aftertreatment is needed to use it in further processes. Besides most of the FB gasifiers need high-quality wood chips and cannot work with residuals from landscape work and agriculture e.g. straw, green waste, leaves.

Entrained flow (EF) gasifiers are state of the art in large scale coal gasification plants [3]. Because of the high operation temperature up to 1500 °C the product gas is almost free of tars and no expensive aftertreatment

system is necessary. On the other hand a homogenous pulverized fuel is needed. It is already shown that EFG can be a competitive alternative to FBG [4]. At the moment only few research groups work on EF biomass gasification [5, 6, 7].

The challenge is to get an almost tar free product gas and to use biomasses which are not used until now. This leads to the approach of a two-stage process:

The first stage is a pretreatment of the feedstock. For wet biomass this could be hydrothermal carbonization (HTC) and for woody biomass torrefaction (TF). It is already known that TF improves the grindability and other fuel properties [8, 9] but it is still the question if this additional process is competitive. The second stage is the high-temperature gasification in an EF.

For research on high-temperature biomass gasification a new EF pilot plant was constructed and commissioned. Design and engineering are described in [10]. The goal is to investigate the gas quality, ash-melting behavior and process efficiency in dependence of the biomass pretreatment and the operating parameters of the high-temperature gasification.

In this work first results using pure oxygen as gasification agent with torrefied wood and raw wood (beech) are described.

2 SET-UP AND MEASUREMENT METHODS

2.1 Set-up of the test rig

The test rig has already been described in [10]. The general plant design parameters are shown in Table I:

In Figure 1 a drawing of the test rig with its main assemblies is presented (dosing system and product gas flare not shown). Biomass is transported by a pneumatic feeding system (N₂ as carrier stream). Feeding system is described more in detail in [11]. Biomass and gasification agent are introduced through a burner unit on top of the gasifier in the reaction chamber. At the end of the

chamber the product gas is quenched by water injection. After filtration the product gas is burned in a flare using a natural gas pilot burner.

Table I: Plant design parameters

Operation mode:	autothermal (with burner)
Temperature:	up to 1500 °C
Pressure:	0 to 5 bar _g
Fuel input:	70 - 120 kW
Gasification agent:	Air, O ₂ , H ₂ O, CO ₂
Fuel feeding:	10 - 25 kg/h

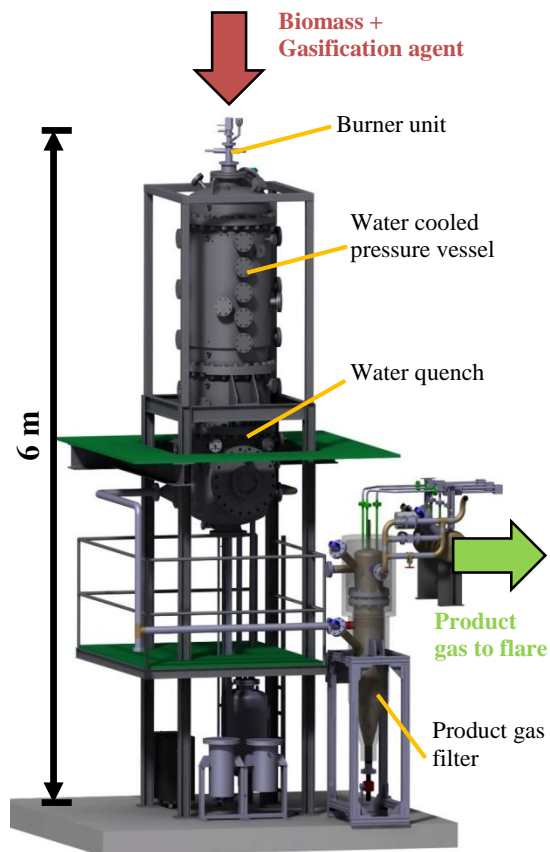


Figure 1: Set-up of the test rig (dosing system and product gas flare not shown)

The design of the test rig is industrial like but still flexible enough to investigate different fuels and operation parameters.

2.2 Measurement and monitoring methods

Figure 2 shows a cross section view of the gasifier. The reaction chamber has an inner diameter of 250 mm and a length of ~ 1.8 m. The main measurement and monitoring methods are shown. These are:

- 6 Thermocouples type R in the refractory distributed over the height of the reaction chamber.
- camera for flame monitoring on top
- movable oil tempered sampling probe for particle sampling and online gas analysis (CO, CO₂, CH₄, H₂, O₂ and H₂O)
- heated sampling probe to take SPA probes for tar analysis (SPA method as described in [12])

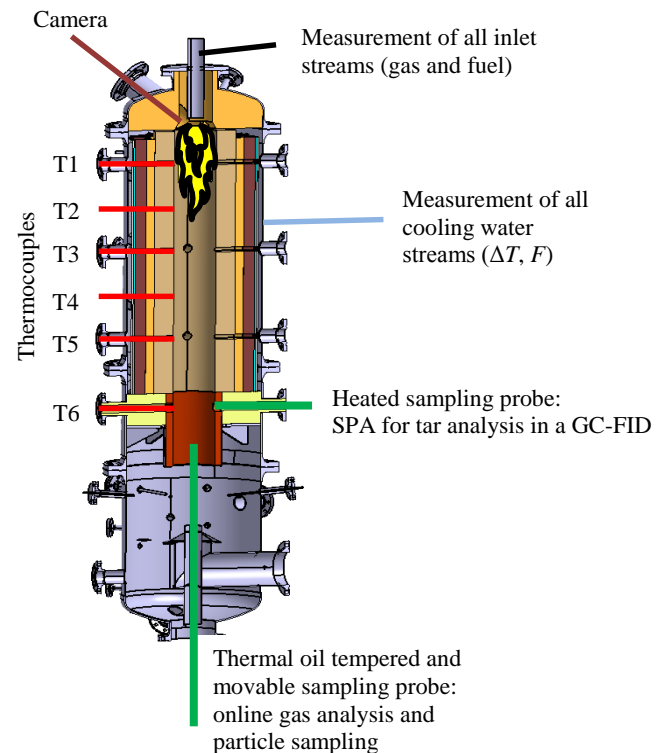


Figure 2: Cross section view of the gasifier with main measurement accesses

3 TRIAL PARAMETERS AND PROCEDURE

3.1 Fuel parameters

In this work two different biomasses are investigated:

Raw wood powder originates from beech wood. The only treatment is milling and sieving. The powder is a commercial product from *JRS J. Rettenmaier und Söhne GmbH und Co KG*, product name *HB 120*.

The torrefied fuel is also a commercial product. It was delivered in pellets which were milled and sieved then to the particle size mentioned in Table II. It is made from a mixture of deciduous and coniferous wood (according EN 14961-1 typ 1.1. forest, plantation and other virgin wood). Torrefaction was carried out at a temperature of 290 °C for 45 min.

Table II shows the complete analysis of both used fuels (chemical as well as mechanical properties).

Table II: Fuel Analysis

	torr. wood	raw wood (Beech)
Ultimate analysis in wt-% (ar)		
C	53.1	48.2
H	5.2	5.2
N	0.6	0.3
S	0.3	0.3
O	31.7	38.3
Proximate analysis in wt-% (ar)		
Moisture	5.5	6.4
Volatile Yield	64.8	78.9
Ash	3.6	1.1
Fixed Carbon	26.2	13.7
Lower heating value in kJ/kg (ar)		
H_u	19724	17311
Particle size analysis in μm		
d_{10}	25	28
d_{50}	103	124
d_{90}	224	263
Bulk density in kg/m^3		
ρ_{bulk}	468	327

3.2 Operation parameters

The trials described in this work were carried out with a thermal firing capacity of ~ 70 kW. Operation parameters are shown in Table III.

Table III: Operation parameters for the trials

	torr. wood	raw wood (Beech)
Fuel input in kg/h	13.0	14.4
Fuel loading in conveying pipe in $\text{kg}_{\text{fuel}}/\text{kg}_{\text{N}_2}$	13.9	8.6
air-to-fuel equivalence ratio λ	0.4	
Pressure in mbar _g	200	
Gasification agent	O_2 (@ 200 °C)	
Losses vessel cooling	~ 12 kW	
Energy input electrical heaters	~ 8 kW	

Due to the lower heating value of the beech wood powder the fuel input to reach the same thermal firing capacity has to be higher. Pre-tests with both fuels turned out that for pneumatic conveying of the raw beech wood powder more N_2 is needed to avoid plugging. In general it can be said that the feeding of the torrefied wood powder was easier and without problems regarding fluidization and pipe plugging. This behaviour of torrefied material compared to raw material has already been published in [9]. But it has to be considered that the used torrefied wood powder was made from pellets and not directly from wood chips.

The losses caused by cooling the pressure vessel and camera were ~ 12 kW for both trials. Compared to the thermal firing capacity of only 70 kW this is a very high value which is attributed to the relatively large outer surface area and the cold cooling water input temperature of ~ 25 °C. In a commercial plant these losses would be much lower. To compensate these losses electrical

heaters in the refractory (position and technical details described in [10]) were turned on during the trials with ~ 8 kW input.

3.3 Trial procedure

Before starting the trials the refractory has to be heated up. This is done by the electrical heaters in the refractory. After around two days the wall temperature of the reaction chamber has reached ~ 900 °C. During the whole trial campaign the reactor is held warm by the electrical heaters also during the weekend. Purge gas is only needed for the camera at this time.

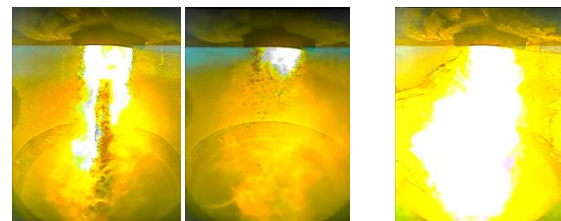
The temperature of 900 °C would be sufficient for the self-ignition of the fuel. But since the operation temperature with pure oxygen is much higher (1100 °C – 1500 °C) the reaction chamber is heated by a gas burner up to the expected trial temperature. The heating time depends on the aimed temperature and is in the range of a few hours.

Due to safety reasons the gasification is always started with air as gasification agent and then switched slowly by sliding a controller to 100 % O_2 .

After reaching stable conditions (minimum 1 h after starting gasification) all process and measurement data are average at least over 10 min of stable operation. Then tar sampling (SPA) is carried out and the filter for sampling particles out of the reaction chamber is mounted in for 10 – 40 min (depending on carbon conversion).

4 OPERATION EXPERIENCES

It turned out that the most important parameter for high carbon conversion and good gas quality is a stable flame. To reach a stable flame a continuous fuel feeding is needed. The camera allows a visual observation of the flame. In Figure 3 examples for a non-stable and a stable flame are shown (same fuel input and λ). If the flame is not stable, the carrier gas (N_2) in the conveying pipe has to be increased. Before using a new fuel for gasification trials it has to be found out which carrier gas amount is the lowest to reach a stable flame and to avoid plugging. If the carrier gas stream is too high the product gas will be unnecessarily diluted with N_2 .

**Figure 3:** left unstable flame, right stable flame

The gasifier was also operated at higher temperatures in slagging mode (ash is molten and forms a slag layer on the wall). Data are not evaluated until now. The reaction chamber is just a straight tube until it ends in the quench. Also it is very hot in the upper part of the gasifier (up to 1500 °C) towards the end of the reaction chamber the wall temperature is not high enough to keep the slag molten (see also Figure 5 temperature drop towards the end). The gasifier will plug with time (especially when the ash content of the fuel is high). In order to prevent

this there a slag drop edge has to be installed in the hot zone of a commercial gasifier so that the slag can directly drop into the quench. Figure 4 shows the slag on the wall in the hot and the cold reaction chamber after slagging trials.



Figure 4: Slag on the wall in the cold (left) and in the hot (right) reaction chamber

5 EXPERIMENTAL RESULTS

Figure 5 shows the temperature for thermocouple 1 to 6 for both fuels. It can be seen that there is no significant difference in trend and absolute values. The average measured temperature in the hot zone (T1 –T5) is 1184 °C for beech and 1172 °C for torrefied wood.

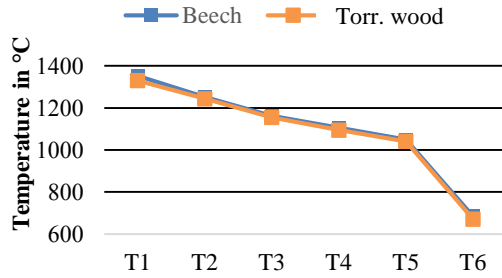


Figure 5: Temperature trend in the reaction chamber

Based on the input streams and the mentioned average temperature a plug flow residence time was calculated. For the torrefied material it is 9.2 s and for beech 8.5 s which is according to same fuel input, pressure and lambda in the same range.

Figure 6 shows the gas composition. Purge gases (necessary for camera and flame detector) are recalculated but not the carrier gas from the feeding system because this is a process parameter which depends on the fuel (cares for stable flame and prevents pipe plugging). The main gas components are shown on a dry basis. N₂ is calculated by difference. H₂O is measured with an additional humidity sensor.

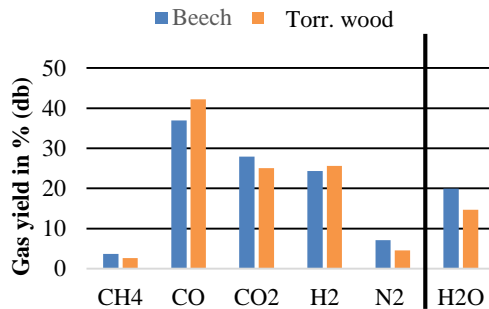


Figure 6: Gas composition for both fuels
These gas compositions lead to lower heating values H_u

of 9,0 MJ/Nm³ for torrefied wood product gas and 8,6 MJ/ Nm³ for beech.

The total tar content is 0.6 g/m³ for torrefied wood and 3.2 g/m³ for beech. This is in accordance to the fact that the product gas of the torrefied material has a lower CH₄ amount than the product gas from beech.

Two important parameters to evaluate the gasification process are carbon conversion (CC) and cold gas efficiency (CGE). Both parameters are calculated on two ways. One way is only by gas analysis (N₂ tracer), the other by ash tracer method.

Via gas analysis (N₂ tracer):

Since the input streams $\dot{V}_{N_2, in}$ of N₂, the mole fraction of all product gas components y_i , and the fuel input \dot{m}_{fuel} are known the carbon conversion CC_{GA} can be calculated by (1) and (2). $x_{0,C}$ is the carbon content (wt.) of the fuel, V_M the molar gas volume (22,41 l/mol) and M_C the molar mass of Carbon (12,01 g/mol).

$$CC_{GA} = \frac{\dot{V}_{syngas} \cdot (y_{CO} + y_{CH_4} + y_{CO_2}) \cdot M_C}{\dot{m}_{fuel} \cdot x_{0,C} \cdot V_M} \quad (1)$$

$$\text{with } \dot{V}_{syngas} = \frac{\sum \dot{V}_{N_2, in}}{y_{N_2, syngas}} \quad (2)$$

The cold gas efficiency is calculated by (3).

$$CGE_{GA} = \frac{\dot{V}_{syngas} \cdot LHV_{syngas}}{\dot{m}_{fuel} \cdot LHV_{fuel}} \quad (3)$$

The assumption for this method is that N₂ behaves inert. (LHV_{syngas} in MJ/Nm³, LHV_{fuel} in MJ/kg)

Via sampled particles (ash tracer):

CC_{ash} is calculated only by of the analysis of the sampled particles (ultimate analysis, water and ash content). The assumption for this method (described in [13]) is that ash behaves inert. If all converted C is present in the product gas as CO, CO₂ and CH₄ and the content of each component y_i is known from the gas analysis \dot{m}_{syngas} can be calculated by (4).

$$\dot{V}_{syngas} = \frac{CC_{ash} \cdot x_{0,C} \cdot \dot{m}_{fuel} \cdot V_M}{(y_{CO} + y_{CH_4} + y_{CO_2}) \cdot M_C} \quad (4)$$

For the CGE (3) can be used again.

In Table IV the calculated CC and CGE are shown. It can be seen that both methods show the same tendency even almost the same values.

Table IV: Carbon conversion and cold gas efficiency

	torr. wood	raw wood (Beech)
CC in %		
Ash tracer	83,6	93
N ₂ Tracer	83,8	91,9
CGE in %		
Ash tracer	55,8	60,7
N ₂ Tracer	56,0	60,0

6 CONCLUSION AND OUTLOOK

The EFG test rig was successfully operated using biomass and pure oxygen for the first time. Torrefied wood and raw beech wood powders were compared. It is shown that generally EFG of biomass with oxygen can lead to a high quality product gas. Under the investigated conditions (70 kW thermal input, $\lambda=0.4$) the torrefied wood shows a lower tar amount, a higher heating value of the product gas and needs less additional N_2 in the fuel conveying pipe. On the other hand beech wood powder shows higher carbon conversion and higher cold gas efficiency. This can be explained by the higher volatile yield of the raw beech wood powder and a higher char reactivity compared to torrefied wood.

For a commercial plant the described operating point is not good enough. CC should be higher and the tar amount of the product gas lower. The data evaluation of the complete trial campaign will result in a broad overview of the influence of λ -variation and also steam addition for different biomasses (beech wood, torrefied wood, hydrothermal treated green cut and corncobs) and will indicate which operation parameters are the best in order to reach high CC , high CGE and low tar amount.

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7 ACKNOWLEDGEMENTS

The financial support from German Federal Ministry of Food and Agriculture (FKZ: 22023911) is gratefully acknowledged. The authors also like to thank all students of TUM, who work on this project.