HIGH-TEMPERATURE BIOMASS GASIFICATION IN AN ENTRAINED FLOW REACTOR – DESIGN AND ENGINEERING OF A TEST FACILITY

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ABSTRACT: For several applications like catalytical conversion or a piston-engine a tar free gas should be available. The state of the art technology for the gasification of biomass is the fluidised bed (FB) gasification. Although this technology is realized in small and medium-scale plants, there is one main disadvantage in comparison to an entrained flow (EF) reactor: Due to the operation temperature < 950 °C the product gas contains a high amount of tars and an aftertreatment to reduce the concentration of tars is necessary.
The aim of this work is to design a high-temperature gasifier to avoid tar in the product gas and to use biomasses which are not used energetically until now. Also they should not compete with the agricultural cultivation of food. Therefor grass-cut, agricultural residuals and straw are of interest. The process is divided into a biomass pretreatment (hydrothermal carbonization or torrefaction) and the EF gasification. The EF gasification is state of the art in industrial coal gasifiers and even can be easier in set-up and handling than a FB gasifier.
A lab-scale EF gasifier (100 kW, pneumatical fuel feeding 10–25 kg/h) was designed and constructed to be operated either with ambient air at 1000-1200 °C or with O_2, CO_2 and/or steam up to 1500 °C and 6 bar a. In order to facilitate a future up-scale and to learn about the conditions and problems of a real process the gasifier is engineered as close as possible to an industrial process. For this reason the gasifier operates autothermal and has a burner system. The reaction tube consists of several layers of refractory. The dimensions of the reaction chamber were defined after kinetic calculations for optimal char conversion.

Keywords: gasification, pilot plant, thermochemical conversion, pretreatment

1 INTRODUCTION

An overall goal of many countries worldwide is to reduce the CO_2-emissions and to produce heat, electrical energy and fuels in a renewable way. This is why the use of biomass for energy supply gets more and more important. In contrast to a solid fuel a gaseous fuel opens the possibility to be used in many different processes, e.g. gas turbine, piston engine, fuel cell, SNG-production. Therefore the conversion of solid biomass to gas is often the first step for the utilization of biomass for power generation or as secondary energy carrier [1]. All the following processes have requirements regarding the gas quality, especially the tar content often is a problem.

The state of the art technology in biomass gasification is fluidized bed gasification. Although several plants are operated with this technology it has one main disadvantage: Due to the low operation temperature (< 950 °C) the tar content of the product gas is very high and an aftertreatment is needed to make it useable in catalytic conversion, combustion engines or other processes. Besides most of the FB gasifiers need clean wood chips and cannot work with residuals from landscape work and agriculture e.g. straw, green waste, leaves.

EF gasifiers are state of the art in large scale coal gasification plants. 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. But on the other hand a homogen pulverized fuel is needed. That EFG can be an economic alternative to FBG is already described in [2]. At the moment only a few research groups work on EF biomass gasification [3, 4].

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 new approach of a two-stage process: The first stage is a pretreatment. For wet biomass this could be hydrothermal carbonization (HTC) and for woody biomass torrefaction (TF). The second stage is the high-temperature gasification.

For the research on high-temperature biomass gasification a new EF pilot plant is constructed. The design and the engineering are described in this paper. The goal is to investigate the gas quality, ash-melting behavior and the process efficiency in dependence of the biomass pretreatment and the operating parameters of the high-temperature gasification, especially gasification agent and pressure. In this work only the EF gasifier is considered but to integrate the high-temperature gasification in a complete process also the pretreatment and the utilization of the product gas e.g. for power generation has to bear in mind all the time.

2 SPECIFICATION SHEET

Before design and engineering can start a clear definition of all requirements is necessary.

2.1 Fuel

The fuel for the high-temperature process is a biocoal from hydrothermal carbonization or torrefied woody biomass. For the process design a biocoal from HTC was chosen. This fuel is an average biocoal. Input to the HTC-process were different biomasses, which are seasonable available during a year (e.g. green waste, leaves). Proximate and ultimate analysis of this HTC-coal were carried out. The results are shown in Table I. The d_{50} particle diameter of this fuel is 53 µm, which is very small. To be on the safe side in further calculations regarding conversion and CGE d_{50} of 150 µm was

assumed. The LHV (dry) is 24.8 MJ/kg.

Table I: Fuel Analysis

Ultimate analysis in wt-% (ar)	
C	59,96
H	3,67
N	0,68
S	0,57
O	20,15

Proximate analysis in wt-% (ar)	
Moisture	11,32
Volatile Yield	55,11
Ash	3,66
Fixed Carbon	29,91

2.2 Plant requirements

The aim of this work is not only to get a broad knowledge about high-temperature biomass gasification itself but also to get experiences in the operation of a future commercial biomass gasification plant. This is why the design has to be industrial-like and as close as possible to a technical realistic facility. This means that the process will be operated autothermal. The energy needed for the endothermic gasification reactions will be provided by partial oxidation of the fuel in a burner system.

On the other hand to investigate the influence of the operating parameters the plant has to be very flexible. A variation of the gasification agent (air, O_2, H_2O, CO_2) and the pressure (from 1 to 6 bar a) should be possible. To give a clear statement over the process mass and energy balances, gas analysis, particle sampling and other measurement technologies are necessary. In this perpesctive the new facility behaves more like a small lab-scale test rig.

The challenge of this work is to negotiate the gap between industrial and laboratory design and to combine both in the new facility.

Table II: Plant specification sheet

Requirements	
Operation mode:	autothermal
Temperature:	up to 1500 °C
Pressure:	1 to 6 bar a
Fuel input:	100 kW (+/- 25 %)
Gasification agent:	air, O_2, H_2O, CO_2
Operation without fuel refilling:	up to 10 h
Design:	industrial like, flexible, easy cleanable/demountable

3 PROCESS DESIGN

3.1 Process flow sheet

The next step is to draw the first process flow sheet and to define all main components. This is done in Figure 1. The most important part of the new plant is the gasifier itself.

3.2 Dimensioning of the reaction chamber

A large scale industrial EF gasifier is usually designed and optimized for one operation point (pressure, fuel, gasification agent). These parameters have a great influence on residence time and conversion. Normally the fuel input increases proportional with the pressure. For our plant 100 kW at 1 bar a means 600 kW at 6 bar a. Due to the large amounts of fuel needed for 600 kW and the fact that all components - especially dosing system, product gas filter / burner and all the valves - have to be able to cover this wide range, it is decided that the normal operation pressure for 100 kW fuel input is defined as 3 bar a. Operation at 1 bar a and at 6 bar a will not lead to optimal conditions but the gasifier will work in an acceptable way by adjustment of some parameters.

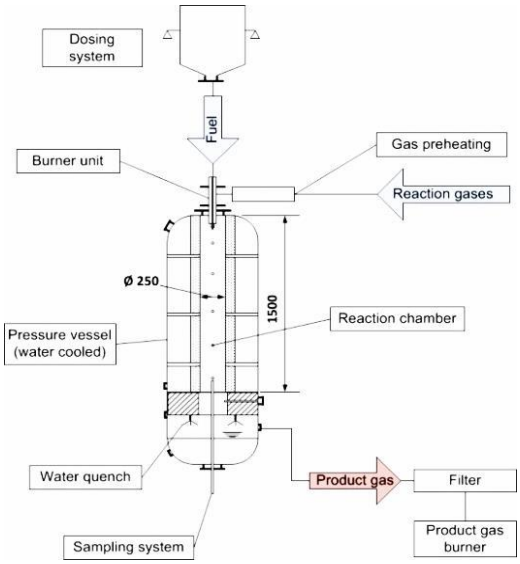

Figure 1: Process flow sheet with main components

To find the right dimensions of the reaction chamber (diameter and length) calculations regarding char conversion were carried out. For the reaction rate a simple kinetic approach was used (1).

$$r_{obs} = r(T) = k_{0,obs} \cdot e^{\left(-\frac{E_{A,obs}}{R \cdot T}\right)} \quad (1)$$

The used model takes into account only the observed reaction rate and not the intrinsic reaction rate. It includes devolatilization as well as homogenous and heterogenous gasification reactions described in [5]. CH_4 generation is not considered. The complete model is described and validated in [6]. Process is temperature is overrated and there are also other disregards and limitations of this simple model but to get a first idea of conversion rate without knowing all fuel parameters in detail it is a good tool.

$k_{0,obs}$ and $E_{A,obs}$ are empirical constants that have to be determined by experimental trials. Until now they are not available for the selected fuel but it is known that the fuel behaves like a lignite. For this reason the parameters were taken from a lignite R [6]: $k_{0,obs}$ is 351 s^{-1} and $E_{A,obs}$ is 64 kJ/mol.

After calculations with varying dimensions, pressure and gasification agents the dimensions of the reaction chamber were defined. The inner diameter is 250 mm and the length is 1500 mm (Figure 1).

Figure 2 shows the calculated char conversion and temperature for the best case (pressure: 6 bar a, gasification agent: O_2/H_2O) and the worst case (pressure: 1 bar a for the chosen dimensions) for 100 kW fuel input and an O/C-ratio (oxygen input / carbon input) of 1. The normal operation point will be in between. In the worst case the char conversion reaches only 81 %, the overall fuel conversion is about 93 %. In the best case 100 % conversion are possible.

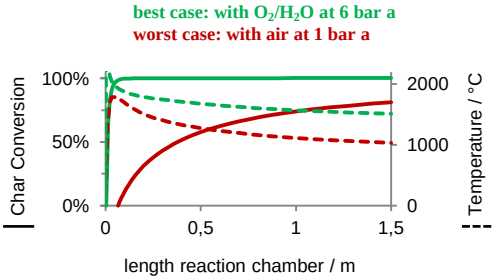

Figure 2: Calculated char conversion and temperature

The calculated product gas composition for both cases is shown in Table III.

Table III: Expected product gas composition

	best case	worst case
H_2	20 %	9 %
CO	44 %	19 %
H_2O	21 %	6 %
CO_2	13 %	8 %
N_2	2 %	58 %

A further optimization is possible by adjustment of operating parameters, e.g. O/C-ratio, steam input, fuel input and by the burner design.

The outer diameter of the reaction chamber is determined by heat loss calculations to 800 mm.

4 DETAILED ENGINEERING AND CONSTRUCTION

4.1 Gasifier

The entrained flow gasifier is the core component of the plant. It is designed in CAD with Catia. The pressure vessel is double layered for water cooling. It is made for 9 bar g and 300 °C and is demountable into 4 parts (Figure 3). The material is stainless steel 1.4571. Manufacturer is *Heger-Edelstahl GmbH, Austria*.

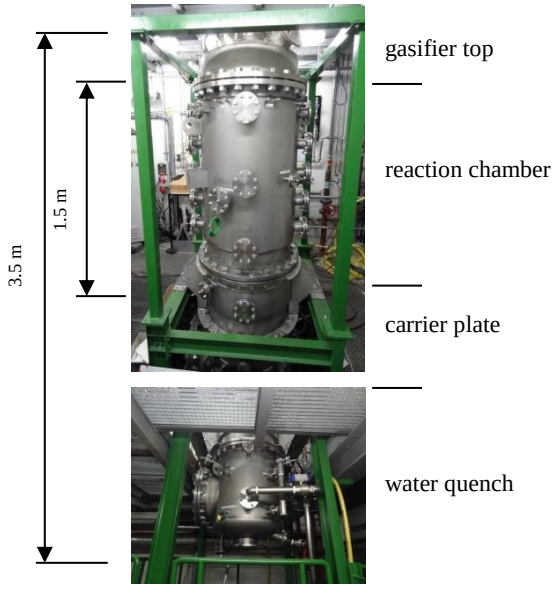

Figure 3: Picture of the gasifier pressure vessel

To reduce heat losses the reaction chamber consists of a multi layer refractory (Figure 4). The inner layer is resistent up to 1800 °C. The layout was created in cooperation with *Rath GmbH, Germany*. The refractory has a total weight of 1.8 t.

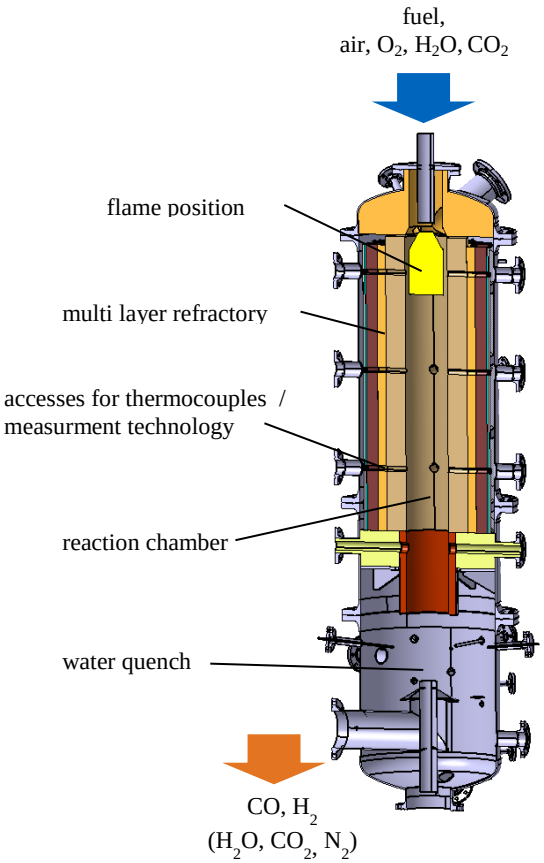

Figure 4: Cross section view of the gasifier

To reach a self-ignition of the biomass without a pilot burner the reaction chamber walls have to be hot before starting the trials. For this reason 8 electrical heaters with 4 kW each are integrated in the refractory (Figure 5). With these heaters the reaction chamber can be heated up to 1000 °C without observation and experiments can start directly after temperature is reached without any changes in set-up. Due to the large mass of the refractory the complete heating up procedure will last around 36 h. But then the reaction chamber will stay hot during the whole trial campaign. To avoid cooling over night the heaters can be switched on with low demand. The electrical heaters are a special-purpose solution from *Carlo Loysch GmbH, Austria.*

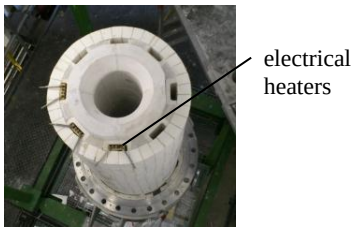

Figure 5: Reaction chamber without pressure vessel

4.2 Feeding system

Besides the gasifier another important component is the fuel feeding system. The feed stream has to be very continuous otherwise the product gas composition and quality would change due to the changing air ratio λ. Furthermore the fuel carrier stream (for safety reasons N_2) has to be as low as possible, because – especially in trials with O_2/H_2O – the N_2 would diminish the LHV of the product gas and it is a large thermal ballast for the process. For these reasons it was decided to use a pneumatical feeding system from *E.S.C.H. GmbH, Germany*. The system can dose from 10 to 25 kg/h pulverized fuel with an amount of only 0.02 m^3_{N2}/kg_{fuel}.

4.3 Other important components

To analyze gas and particles from the reaction chamber a sampling probe is engineered, which is able to take gas and particle probes in different levels of the reaction chamber. Due to the high temperature the sampling probe is made out of the heat resistant stainless steel 1.4876 and it is oil cooled. The particle sampling operates isokinetically.

In order to reach a safe and automated operation a PLC Simatic S7 from *Siemens AG* is used. It is made both for the controlling of the process and for data logging of the results. All mass and energy streams are measured, so the balances can be closed online.

Although a water quench is used to cool down the product gas there still can be some particles. They could sediment in the pipes and damage the valves. For this reason a ceramic candle filter was installed. After the gas is filtered, it is burnt in a flare on the roof. A natural gas burner serves as pilot.

5 OUTLOOK

The first heating up with a defined heating curve (84 h program) will take place in August 2014. First trials with HTC-coal are planned for September 2014.

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