STUDY OF A DECENTRALIZED ENTRAINED-FLOW GASIFICATION PLANT IN COMBINATION WITH BIOMASS FROM HYDROTHERMAL CARBONIZATION FOR CHP

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ABSTRACT: In this paper a new approach, consisting of hydrothermal carbonization in combination with gasification in an entrained-flow process for combined heat and power in a gas engine is investigated. Main advantage of such a system are the low consumption costs resulting from the type of applicable feeding materials that are not usable with state of the art technologies. In the first part a highly integrated plant for the production of biocoal with hydrothermal carbonization is investigated with a plant size of 16 MW of biocoal production. The process is modeled in Aspen Plus® in order to determine energy and material flows as well as to optimize the heat integration of the system. The decentralized utilization of biocoal from hydrothermal carbonization in an entrained-flow gasifier is simulated for a plant size of 1.6 MW biocoal input. Efficiencies of the heat and power generation are calculated for individual components and the whole process chain. Power can be produced with an overall electric efficiency of 26 %.

Keywords: hydrothermal carbonization, simulation, biomass, gasification, CHP, biocoal

1 INTRODUCTION

Facing the challenge of the transition to a sustainable and eco-friendly energy production, innovative technologies need to be investigated. The utilization of domestic biomasses and residues plays an important role in a flexible and independent supply of energy in the form of heat and power.

Today's technologies for heat and power generation with biomass for decentralized applications focus mainly on high quality fuels like wood. Thus the market for these is depleted. An upgrading process can be applied to make less valuable biomasses accessible for high efficient energy conversion systems. Different upgrading processes, e.g. torrefaction, pyrolysis or hydrothermal carbonization (HTC), are known and under research. Unlike torrefaction or pyrolysis the HTC process takes place under wet conditions. That makes it especially suitable for biomasses with high water content.

The process of hydrothermal carbonization is an artificial coalification process that has been investigated by Bergius [1] in 1913. During the HTC several reactions (hydrolysis, decarboxylation, dehydration, condensation and aromatization) take place resulting in increased carbon content in the dry substance [2]. Biocoal made from HTC is hydrophobic and can be dewatered mechanically to a low water content compared to the raw materials thereby energy needed for thermal drying is reduced.

For power generation the produced biocoal is converted to syngas in an entrained-flow gasifier. Although entrained-flow gasification is typically applied at large scale in the range of several 100 MW_{th} it has been shown that it can be competitive at smaller scale as well [3]. During HTC process the biomass structure is destroyed facilitating the grinding of the biocoal to a dusty consistence which is needed for entrained-flow conditions. The syngas is used for combined heat and power (CHP) in a gas engine.

To achieve a profitable industrial-scale realization the energy efficiency of the whole process must be considered. In this paper process integration for a plant size of 16 MW biocoal production is investigated that combines energy yield and demand of the HTC and the drying process. Beside the production of the biocoal at a larger scale HTC plant the gasification and the CHP plants are assumed to be applied decentralized for local heat distribution networks.

2 HYDROTHERMAL CARBONIZATION OF BIOMASS

2.1 Feeding materials

Different sources can be applied as feedstock. In this study the availability of biomass was assumed to vary during the year. Fig. 1 shows the composition of feeding materials as expected. Calculations were made for a reference mix that is averaged over the whole year.

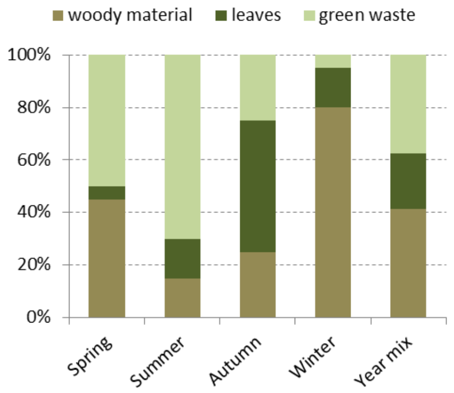

Figure 1: Seasonal availability of feeding materials for HTC process

The composition of the assumed yearly averaged mix of the biomass and the resulting biocoal are calculated and listed in form of an ultimate analysis on a dry basis (db) in Tab. I. It can be seen that the amount of carbon increases while the oxygen decreases resulting in a enhanced heating value (LHV).

Table I: Ultimate analysis, %wt (db)

	biomass	biocoal
C	47.3	59.13
H	5.82	6.35
N	0.88	0.90
S	0.12	0.08
O	41.12	29.23
LHV (MJ/kg)	17.71	23.72

2.2 Simulation model of HTC plant

In this work no reaction model for the HTC process itself is presented. The HTC process is modeled in Aspen Plus® as a “RYield”-reactor using process data from Suncoal Industries GmbH. Balancing the inputs and outputs a change in the enthalpy can be determined and thus the energy released by the exothermal HTC reactions.

According to [4] the HTC process can be described with some characteristic parameters that are calculated on a dry basis. The mass yield µ represents the mass loss of the dry matter during conversion from biomass (BM) to biocoal (BC).

$$\mu = \frac{m_{BC,dry}}{m_{BM,dry}}$$

ψ is the increase in heating value.

$$\psi = \frac{H_{U,BC}}{H_{U,BM}}$$

Both together define the efficiency of the HTC process:

$$\eta_{HTC} = \psi \cdot \mu$$

In Tab. II the process data for HTC are summarized. With the efficiency of the HTC process and the heating values of the biomass the specific reaction heat can be determined as

$$q_R = (1-\eta_{HTC}) \cdot H_{U,BM}$$

The resulting specific reaction heat is 1.55 MJ/kg based on biomass input and therefore represents a realistic value compared to literature [4, 5]. It has been assumed that the heat of the exothermal reactions could be used for heat recovery.

Table II: Parameters of HTC process

$\eta_{HTC} = \psi \cdot \mu$	$\psi = \frac{H_{U,BC(db)}}{H_{U,BM(db)}}$	$\mu = \frac{m_{BC,dry}}{m_{BM,dry}}$
91.22	128.06	71.23

The model for the HTC plant is shown in Fig. 2. Biomass (1) is pre-heated in several steps to achieve the HTC conditions of 20 bar and 200 °C in the reactor (4). For pre-heating the exhaust steam of the thermal dryer (10) is being condensed (2) and mixed with recirculated water from the mechanical drying (9). In the following steps steam that is recovered from flashing the slurry (5-8) leaving the reactor, is added for further pre-heating. To prevent boiling intermediate pressurization is needed so that pre-heating is done at 4 pressure levels. To reach final HTC conditions additional heat is provided externally at (3).

After mechanical drying in a membrane filter press (9) a cake with a water content of 49 %wt is dried in a thermal dryer (10) to its final water content of 5 %wt and exits the process as biocoal (11). The thermal drying is modeled as a fluidized bed dryer with steam as fluidizing medium. Additional steam (14) is produced from the waste heat of the HTC reactor and used as heat input by heat exchangers in the fluidized bed. The missing amount of energy is provided by an external heat exchanger (15).

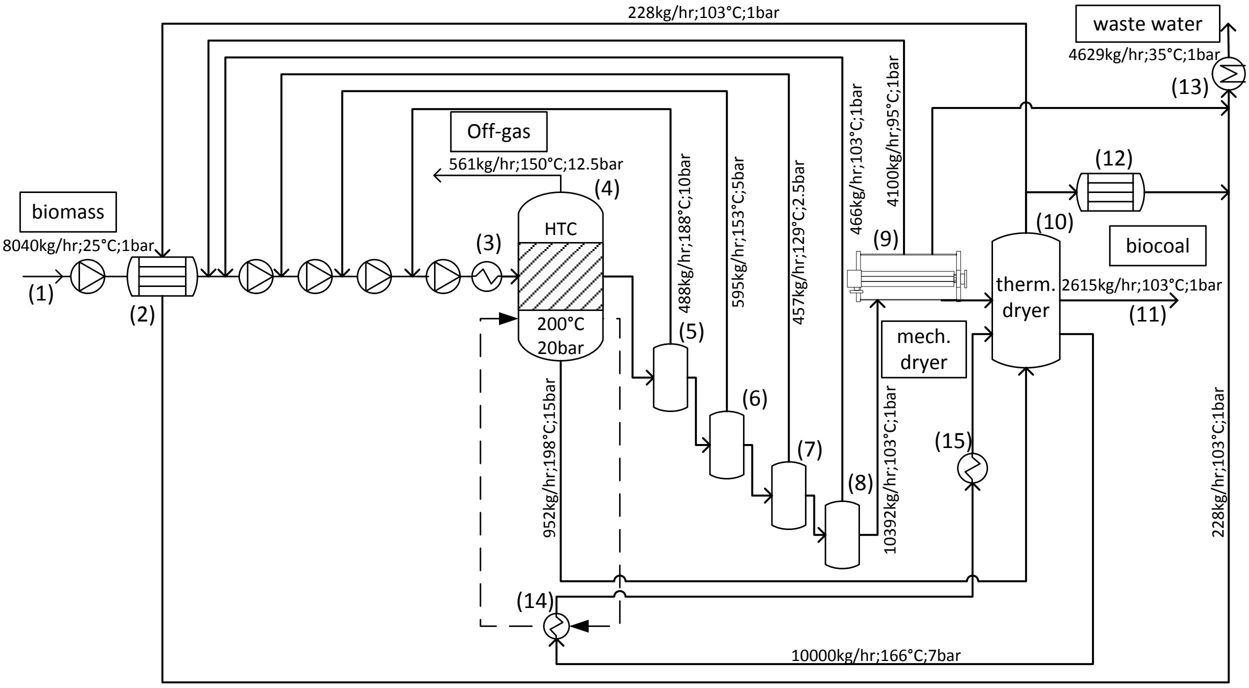

Figure 2: Schematic model of the simulated HTC plant

Steam from the thermal drying that cannot be used inside the process is condensed (12) and cooled (13) together with the waste water for the waste water treatment that is not considered here.

2.3 Results and evaluation of the HTC plant

The process is analyzed with regards to additional required heat that cannot be provided inside the process. In Tab. III the heat and power required externally are summarized. Other heat sources are not needed due to an almost complete heat recovery system. The feasibility of heat exchange was proven utilizing the software Hint for pinch point analysis [6].

Table III: Required additional heat and power sources not covered internally

No.	Description	Heat / Power [kW]
3	heat for pre-heating of biomass	407
15	heat for thermal drying	217
9	electric power for filter press	12
4	electric power for HTC/pumps	130
10	electric power for thermal dryer	112

For the evaluation of the HTC plant an efficiency factor is defined that takes into account the energy of biomass and biocoal as well as additional heat required for drying and pre-heating. Also electric consumers are considered as shown in Tab. III.

$$\eta_{HTC-plant} = \frac{\dot{m}_{BC,dry} \cdot H_{U,BC(db)}}{\dot{m}_{BM,dry} \cdot H_{U,BM(db)} + P_{el} + Q_{heat}}$$

The calculated overall efficiency of the HTC plant is 86.92 %. Erlach et al. [7] have calculated the overall efficiency of a real HTC plant to be 82.42 % using the higher heating value of the fuel and the biomass. This gain in efficiency can be partially explained by neglected heat losses. But mainly the increase is due to the complex heat integration of the drying process.

3 ENTRAINED-FLOW GASIFICATION OF BIOCOAL FROM HTC FOR CHP

3.1 Description of the gasification and CHP plant

In most large scale entrained-flow gasification plants oxygen is used as gasification medium and thus an air separation unit (ASU) is required [8]. However for decentralized biomass utilization small scale plants are needed. In this paper a CHP plant is investigated with an output of 500 kW_{el}. The gasifier operates at atmospheric pressure aiming for a reduced complexity of the system. As gasification medium air is used to avoid high costs for the ASU.

Fig. 3 shows a schematic concept of the gasifier with a gas engine CHP. Biocoal (263 kg/h; 1.65 MW) from HTC is ground and pneumatically fed into the gasifier together with air. The resulting syngas is cooled down in two steps for pre-heating the air (76 kW) and providing heat for district heating (150 kW). After gas cleaning the cold gas is burned in a gas engine producing power and heat. Thermal losses of the gasifier are assumed to be 1 % of the energy input which corresponds to a refractory wall design [13].

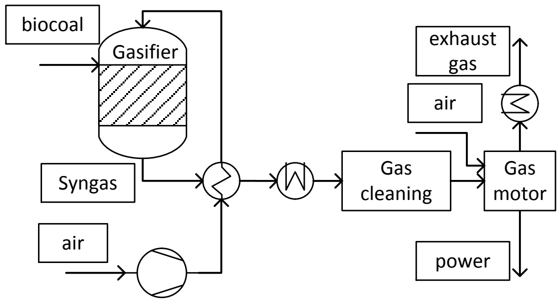

Figure 3: Schematic concept of the gasification plant for CHP with a gas engine

3.2 Syngas quality from entrained-flow gasification

Compared to allothermal gasification syngas from autothermal gasification, e.g. entrained-flow gasification, leads to syngas with a low heating value. In addition gasifying with air dilutes the syngas with nitrogen. Achievable heating values are in the range of 2-5 MJ/kg without and 6-7.5 MJ/kg with pre-heating of the air [9].

For these comparatively lean gases special requirements towards the gas engine must be taken into account. An optimization of the process concerning the syngas quality was done by varying the stoichiometric oxygen to fuel ratio λ. Fig. 4 shows the effect of varying λ on the LHV of syngas and the outlet temperature of the gasifier with pre-heating of the air to 500 °C. It was assumed that for a complete conversion of carbon an outlet temperature of 1.000 °C is necessary and thus an air-fuel equivalence ratio $\lambda = 0.35$ was chosen corresponding to an LHV of 5.1 MJ/kg.

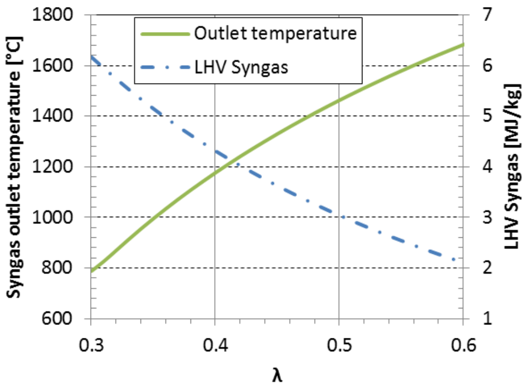

Figure 4: Effect of *λ* on LHV and outlet temperature of the syngas

The efficiency of the gasification process can be determined by the cold gas efficiency (CGE) [8]:

$$\eta_{CGE} = \frac{\dot{m}_{syngas} \cdot H_{U,syngas}}{\dot{m}_{BC,dry} \cdot H_{U,BC(db)}}$$

In Tab. IV the gas composition of the syngas is shown. The formation of other gas components was neglected in accordance to experimental results from entrained-flow gasification in literature [10, 11].

Table IV: Gas composition of the syngas from gasifier

Gas	H_2	CO	H_2O	CO_2	N_2
vol.-%	18.6	26.9	3.3	4.1	47.1

The cold gas efficiency of the gasification plant with pre-heated air is 80 %.

3.3 Evaluation of gas engine CHP

The suitability of syngas for a motor application must be evaluated. Therefore the heating values of the mixtures of combustion air with syngas and with methane are calculated and compared. Assuming $\lambda = 1.2$ the $LHV_{syngas,mix}$ is 2.35 MJ/Nm³ while $LHV_{CH4,mix}$ is 2.88 MJ/Nm³. By increasing λ the difference in LHV decreases due to the influence of nitrogen from combustion air.

In [12] the performance of a combustion engine was investigated with a similar producer gas as in this paper. Compared with natural gas and diesel the performance of the engine slightly decreases and an efficiency of 20 % was reached. This value represents a lab scale engine. With specially designed turbocharged engines electric efficiencies of 36 % are attainable and therefore assumed for the efficiency analysis.

Thermal efficiency is assumed to be 49 % so that the CHP plant is capable of producing 475 kW_{el} and 647 kW_{th}. For the evaluation of the whole technology chain the heat of the syngas cooling must be considered as well. In Tab. V the different efficiencies are summarized relating to the engine and the CHP plant including gasification.

Table V: Efficiencies of the engine and the gasification CHP plant for heat and power production

$\eta_{th,motor}$	$\eta_{el,motor}$	$\eta_{th,CHP}$	$\eta_{el,CHP}$
49	36	48.8	28.9

4 CONCLUSION

In this paper a new approach has been investigated for decentralized utilization of biomass residues based on the combination of the HTC technology and entrained-flow gasification for motor use. A HTC plant with highly efficient heat integration was simulated in Aspen Plus® for a plant size of 16 MW biocoal production.

For CHP an entrained-flow gasification process with gas engine utilization was simulated for decentralized application with a fuel input of 1.65 MW.

Taking into account the whole technology chain including HTC biomass conversion, gasification and power generation an overall electric efficiency of 25.4 % has been calculated. The thermal efficiency of the whole process is 42.67 %. For small-scale applications these values are comparable to state of the art biomass utilization technologies.

The great potential of the proposed system is that it is capable of using biomasses which are not used energetically yet and therefore are cost-efficient. In the present work no detailed simulation of the gas cleaning for the syngas from gasification could be made. Experimental work is planned to be done for the configuration of a gas cleaning system suitable for motor application.

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