SIMULATION AND OPTIMIZATION OF A BIOMASS GASIFICATION PROCESS

Kaiser, S.[1*] Weigl, K.[2]; Schuster, G.[1]; Tremmel, H.[2]; Friedl, A.[1]; Hofbauer, H.[1]
[1]...Vienna University of Technology, Institute of Chemical Engineering; A-1060 Vienna, Getreidemarkt 9/159
[2]...AE Energietechnik GesmbH, A-1211 Vienna, Siemensstr. 89
*...Author, to whom correspondence should be sent: phone: +43 1 58801/159 21 or email: skaiser@mail.zserv.tuwien.ac.at

ABSTRACT: The FICFB gasification process is a special concept of a twin fluidized bed gasifier. The gasification of the biomass and the combustion of the remaining char can be divided into two zones to provide a hydrogen rich product gas with a LHV of 10 - 15 MJ/m³$_S$. This gasification process has to be integrated into a decentralized CHP plant. Scope of this work is to simulate and to optimize the power plant process. Therefore an enhanced equilibrium model, considering the devolatilization of the biomass has been designed. This model yields good results concerning the energetic view of the process. It can be shown, that an electric efficiency of about 26% can be achieved with a simple power plant process. Nevertheless the efficiency can be increased up to 35% with some improvements resulting in higher investment costs for the plant.

1. INTRODUCTION

Biomass gasification has a significant environmental benefit due to a highly efficient energetic utilization of renewable resources, provides net zero carbon dioxide emissions and therefore contributes positive to the limitation of greenhouse gas effects. There are different ways to supply the endothermic gasification reactions with energy. One of them is the partly combustion of the biomass. Disadvantage of this method is a poor product gas quality with a LHV of 4-7 MJ/m³$_S$. Gasification with pure oxygen produces higher quality product gas (10 - 18 MJ/m³$_S$) with the disadvantage of a necessary, expansive oxygen production. Another method of producing high quality product gas is the FICFB gasification process.

The FICFB gasification process [1] is a special concept of a twin fluidized bed gasifier (Figure 1). The biomass is fed to the gasification zone which is designed as a bubbling fluidized bed. Steam is used both as fluidization and gasification agent.

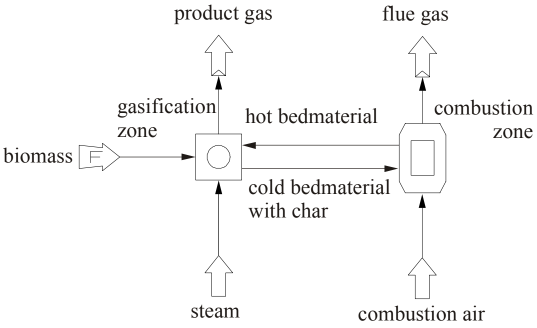

Figure 1: concept of the FICFB gasification process

The bedmaterial, usually quartz, is transported from the gasification zone to the combustion zone carrying ungasified char. The combustion zone operates in fast fluidization regime. Hot bedmaterial leaving this zone is separated by a highly efficient cyclone. To avoid mixing of product gas and flue gas the bedmaterial passes a seal loop before recycling into the gasifier. The hot bedmaterial from the combustion chamber supports the endothermic gasification reactions with energy.

2. MODELING OF THE GASIFIER

Numerous models of fluidized bed gasifiers have been developed and reported in literature. Gururajan [2] gives an overview about different models which can be divided into thermodynamic equilibrium and kinetic rate controlled models.

For the simulation of power plants with an integrated FICFB gasifier, a gasification model with a good prediction of the thermodynamic aspects, also providing good estimates of product gas composition, is essential. According to most authors H_2, CO, H_2O, CH_4, CO_2 and char are described as the most important components of the product gas.

2.1 DRYING AND DEVOLATILIZATION

Due to the high content of volatiles in the biomass it is important to consider the devolatilization step of biomass conversion. Because drying and devolatilization are fast, compared to residence time of a particle, these conversion steps are assumed to be instantaneous. There are a few models for predicting the composition of volatiles from coals. Due to the wide range of different biomasses there is no general model for prediction of their volatiles composition.

A simple modeling approach from Bettagli et.al. [3] was used for prediction of composition after devolatilization. The following assumptions [3] were made:

- the molar ratio of remaining char and CH_4 is 3,
- no CO_2 is formed and
- the molar ratio of H_2O and CO is 1.

The composition of the devolatilization product can be calculated now using the above assumption and the mass balances of the elements C, H and O.

2.2 GAS COMPOSITION

In a first step the model calculates the composition of the devolatilization gas. Volatiles and fluidization agent react with the remaining char to the gasification products. Because of the finite residence time of the gas in the gasifier equilibrium concentration can not be reached.

Table I: Considered reactions, most sensitive component in each reaction and the dimensionless reaction progress

	reaction	sens. comp.	ξ^*
1	$C+H_2O \rightarrow CO+H_2$	char (S=2.94)	0.64
2	$C+CO_2 \rightarrow 2CO$	CO_2 (S=1,03)	1.0
3	$C+2H_2 \rightarrow CH_4$	CH_4 (S=0,52)	0.05

To estimate the gas composition, three linearily independent gasification reactions are required to calculate the concentration of the six considered components. This will fulfill the mass and energy balances which is the most important demand for modeling the thermochemical converison. For each of these reactions a dimensionless reaction progress ξ^* is determined. A reaction progress of 1 means, that volatiles, fluidization agent, biomass moisture and char reacts until equilibrium is reached, a ξ^* of 0 means no progress of this reaction. Equilibrium composition is calculated by minimizing free Gibbs enthalpy [4].

A sensitivity analysis of the dimensionless reaction progress was made to examine, which components should be used for fitting the model (see Table I.). Sensitivity S of x (for example efficiency, composition, ...) versus the parameter ξ^* is given by

$$S = \frac{\Delta x / x_0}{\Delta \xi / \xi_0}$$

Using the experimental data gained from the 100kW FICFB gasifier at the University of Technology Vienna, Institute of Chemical Engineering, Fuel and Environment Technology the dimensionless progress of each reaction was calculated and used for further simulations. Figure 2 shows the results of the model at different steam biomass ratios compared with experimental data. It can be seen, that the model provides satisfying results in a range of a steam biomass ratio of 0,3 to 0,7 kg H_2O/ kg dry biomass.

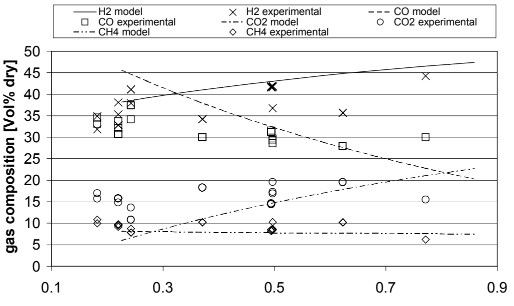

Figure 2: Comparison of experimental and predicted data

The dimensonless reaction progress was varied in a range of 20% to examine the influence on thermochemical conversion, which can be described by the chemical efficiency η_{chem}.

$$\eta_{chem} = \frac{(\dot{m} \cdot LHV)_{productgas\_into\_machine}}{(\dot{m}_{biomass} \cdot LHV_{biomass})_{gasifier}}$$

Sensitivity of the chemical efficiency against variation of ξ^* is very small (0,12) in the viewed range, therefore the model is appropriate for an energetic analysis of the process.

2.3 COMBUSTION CHAMBER

In the combustion chamber the char carried with the recycling bedmaterial and also auxiliary fired fuels (partially recycling of product gas, wood, ...) are burnt to supply energy for the endothermic gasification reactions. Auxiliary firing is necessary to control the gasification temperature at different mass flows of char from the gasifier to the combustion zone. Combustion is assumed to be completely.

3. SIMULATION OF THE PROCESS

Calculations are done by implementing the described model into an equation oriented process simulation environment with a modular structure (IPSE Pro™ [5]) to offer flexible handling of the unit operations. The software contains a development tool which allows to implement user-defined models like gasifier, scrubber or gas engines as well as integrating the calculation of the exergy of all streams.

Decentralized heating and power plants should be of simple design to minimize investement costs. The basic flowsheet of the process is shown in Figure 3. Biomass is fed to the gasifier which is fluidized with steam. The gasification temperature should be above 800°C to reduce tar emissions.

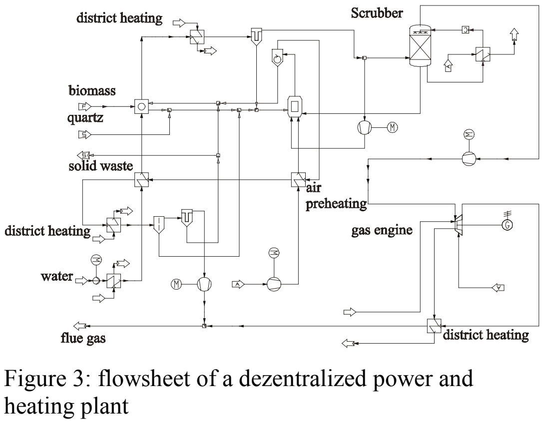

Figure 3: flowsheet of a dezentralized power and heating plant

To avoid exergy loss in the gasifier the gasification temperature is 850°C. Afterwards the gas is cooled down. In a baghouse filter and a scrubber dust (about 30g/m^3_S) and tar (about 1g/m^3_S) are removed [8]. Condensate from the scrubber, which contains the removed tars, is recycled into the combustion chamber to crack tars.

The machine is supplied with product gas for electric power generation. The exhaust gas of the engine is also cooled down in a district heater. The combustion chamber is fluidized with preheated air, the flue gas is used for heat integration.

Table II: main parameters of the decentralized power plant

thermal input	8 MW
gasification temperature	850°C
steam biomass ratio	0.3 - 0.7 kg/kg
district heating power	4.1 MW
electric power output	2.0 MW
water content of biomass	10%

3.1 POWER CONVERSION

Different machines were examined in these studies. Available gas turbines with an electrical output between 2 and 3 MW have the disadvantages of low electric efficiencies (about 26%) and the necessity of a compression step. Available gas turbines are designed for electric power production from high pressurized natural gas. The product gas must be pressurized for combustion in the gas turbine, therefor the net electric efficiency of the gas turbine is much lower (about 24%). Therefore a gas engine with an net electric efficiency of about 37%

$$\eta_M = \frac{P_{generator}}{(\dot{m} \cdot LHV)_{productgas\_into\_machine}}$$

was chosen as machine. The higher CO emissions of gas engines can be avoided by using a catalytic converter, located after the engine heat exchanger..

3.2 RESULTS OF THE SIMPLE PROCESS

With this simple process a chemical efficiency of 71% can be reached, resulting in an electric efficiency of almost 26%. More than 53% of the thermal power can be used for district heating.

$$\eta_{el} = \frac{P_{generator}}{(\dot{m} \cdot LHV)_{biomass}}$$

3.3 EXERGETIC ANALYSIS OF THE PROCESS

Exergy is the part of the energy of a stream which can be transformed into all forms of energy [7]. The exergy of enthalpy of a stream can be calculated as a function of enthalpy h, entropy s and ambient conditions (index a) of the stream.

$$e = e_a + h - h_a - T_a \cdot (s - s_a)$$

The exergy at ambient conditions can be calculated from property tables [6] and is similar to the GHV.

4. RESULTS AND DISCUSSION

It can be seen in Figure 4 and Figure 5 that most of exergy loss results from the gas engine (28%of total exergy loss) and the combustion zone (17% of total exergy loss) due to irreversible combustion reactions.

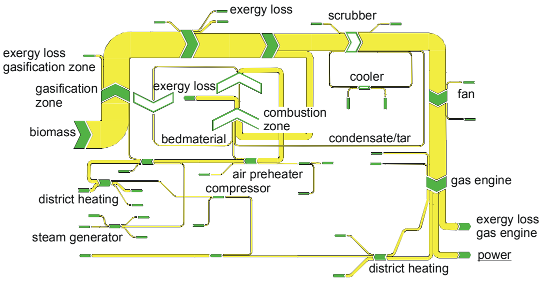

Figure 4: flow sheet of the exergy in the process

13% of the total exergy loss in the process is caused by irreversible heat exchange from hot gases to district heating. 9% of the total exergetic loss has to be assigned to the gasification zone due to evaporation of the moisture of the biomass and irreversible gasification reactions.

An analysis has to be made whether the losses are avoidable or not. The losses regarding the gas engine are only reducable by new developements in gas engines or by using a fuel cell for power generation. It has to be examined whether the high efforts in gas cleaning make this way practicable.

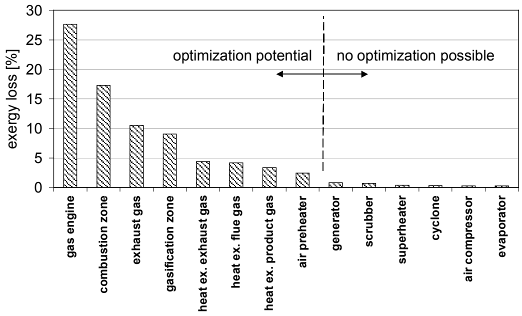

Figure 5: exergy loss in the process

4.1 THERMAL POWER OF HOT STREAMS

A way to reduce the exergetic losses of the heat exchangers is to use the exergy of enthalpy not for district heating but to provide heat for a steam cycle for power generation. This may not be economic for plants with a thermal power of 8MW but for larger plant sizes. The advantage of the gas-engine/steam-turbine cycle using the FICFB gasification concept is the possibility of using the hot flue gas from the combustion zone as well as the exhaust gas from the engine for steam generation.

Using a simple steam cycle (350°C/60 bar) (see Figure 6) and 70% of the flue gas from the combustion zone the electric efficiency can be increased by about 7% to 33%.

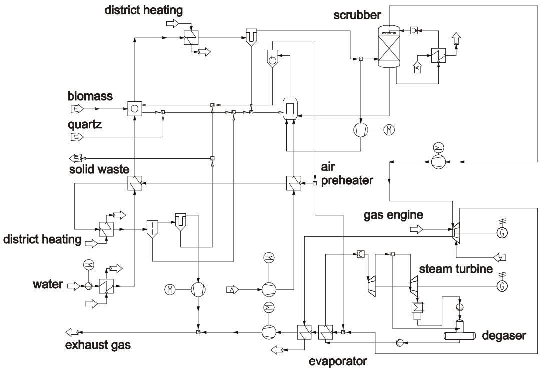

Figure 6: Process using the thermal power of flue gas and exhaust gas for steam generation.

4.2 COMBUSTION ZONE

A detailed analysis of the exergy loss in the combustion zone shows, that about 60% of the total exergy loss is caused by the irreversible reactions in the combustor. The remaining loss can be allocated to the evaporation of condensate from the scrubber and the heating of the combustion air which results in a increase of the electric efficiency of about 1%. The loss due to the air can be reduced by higher preheating temperatures and by reducing the excess air ratio λ in the combustion zone.

Chemical efficiency η_{el} can be raised by 4% increasing the preheating temperature by 100°C. The energetic benefit results in higher investment costs for the heat exchangers due to more expansive materials. A preheating temperature of 300 - 500°C seems to be a good compromise. The air fuel ratio should be minimized to increase efficiency but to reach low CO emissions.

The condensate recycled from the scrubber can be evaporated in an external evaporator supplied with heat from the hot product gas. This will increase the electric efficiency by about 1.5%. Technical risks concerning this procedure are not considered.

4.3 GASIFICATION ZONE

The exergy loss of the gasification zone depends strongly on the water content in the biomass. The irreversible chemical reactions are causing 6% of the total exergy loss, while the remaining exergy loss of the gasification zone increases strongly with the water content. Therefore biomass drying is recommended at higher fuel moistures. The exergetic loss in the gasification zone can be reduced e.g. by using additional fuel instead of product gas for control of the gasification temperature. The exergetic loss of the product gas, which is recycled into the combustion chamber can be avoided resulting in a reduction of the exergy loss of the gasifier. Therefore the electric efficiency is increased by 2%. A flowsheet of this process is shown in Figure 7.

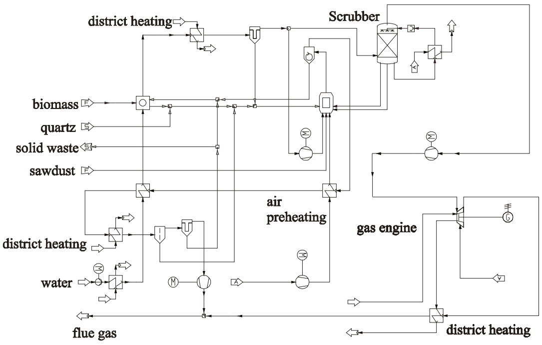

Figure 7: using additional fuel for temperature control

5. CONCLUSION

A simple model of the FICFB gasification process was designed, which provides satisfying results regarding the thermochemical conversion of the biomass. It has been shown, that a simple power generation process with a gas engine can reach an electric efficiency of almost 26%, also providing more than 50% of the thermal power for district heating. For analysis of the process the calculation of exergy was implemented into the simulation program. The loss due to irreversible combustion in the gas engine can only be reduced using new technologies such as fuel cells or new developements in gas engines and turbines.

The exergetic loss caused by using high temperature heat for district heating can be avoided by integrating a steam cycle/turbine into the process. Because of the concept of the FICFB gasifier the electric efficiency can be raised by 7% with a simple steam cycle.

Improving the temperature control of the gasifier can increase the efficiency as well as an external evaporation of the recycled condensate to obtain electrical efficiencies of almost 29%. So high efficient decentralized CHP plants can be realized using the FICFB gasification process and a modern gas engine.

The concept of the FICFB process will be realized now in a demonstration plant in Güssing, Austria also based on these thermodynamic considerations.

ACKNOWLEDGEMENT

Financial support from the Austrian funds program "K_{net}" is gratefully acknowledged.

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