1 MW Scale-up of the Advanced Fuel Flexible Dual Fluidized Bed Steam Gasification Process by Process Simulation

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Abstract

Through the dual fluidized bed (DFB) steam gasification process, solid feedstock can be converted into a nitrogen-free product gas. Thereby, the DFB steam gasification offers a well-proven technology to produce heat, electricity, secondary liquid or gaseous energy carriers and valuable chemicals from wood as feedstock. DFB steam gasification was demonstrated for the gasification of wood at industrial scale between 8-32 MW fuel power at several sites. However, some of these plants suffered from difficult economic conditions if high-grade wood chips or even pellets were used as solid fuel. During the last years, a main research topic has been the utilization of low-cost residual and waste derived feedstocks. Therefore, a fuel flexible advanced reactor design was developed and constructed with 100 kW fuel power at TU Wien and tested since 2014. On the one hand, utilizing residues and waste fractions as feedstock provides a high potential to produce energy carriers, or commodities in a sustainable, eco-friendly and economic way. On the other hand, these feedstocks often have challenging fuel properties for thermo-chemical conversion processes. Although, various feedstocks were already tested at 100 kW fuel power, further investigations need to be done to prove or disprove operation stability at long-term test runs. For this reason, a scale-up to 1 MW fuel power is suggested to further study the long-term behavior of selected promising feedstock. The aim of this study is to provide design data for a basic engineering and to calculate key indicating parameters of a 1 MW fuel flexible plant.

1. Introduction

Through the dual fluidized bed steam gasification process, solid feedstock can be converted into a nitrogen-free product gas (PG). The medium calorific dry PG consists mainly of hydrogen, carbon monoxide, carbon dioxide, methane and ethylene. Basic information on the DFB process can be found in [1]. The DFB steam gasification offers a proven technology to produce heat, electricity, secondary liquid or gaseous energy carriers and valuable chemicals from wood as feedstock [2].

DFB steam gasification was demonstrated for the gasification of wood at industrial scale between 8-32 MW fuel power at several sites [3]. However, some of these plants suffered from difficult economic conditions if high-grade wood chips or even pellets were used as solid fuel - especially because the wood prices increased significantly over the last decade. Figure 1 shows the development of wood chip prices in Germany between 2003 and 2018. As indicated, the price for woodchips increased in Germany until 2015 by roughly 110 %. However, the green feed-in tariffs for electricity and district heat from biomass were not adapted accordingly to that price increase, which led to uneconomical operation and plant shut down for many plant operators depending on wood-based fuels. It seems that the last three years of the considered timespan the strong constant upward trend leveled.

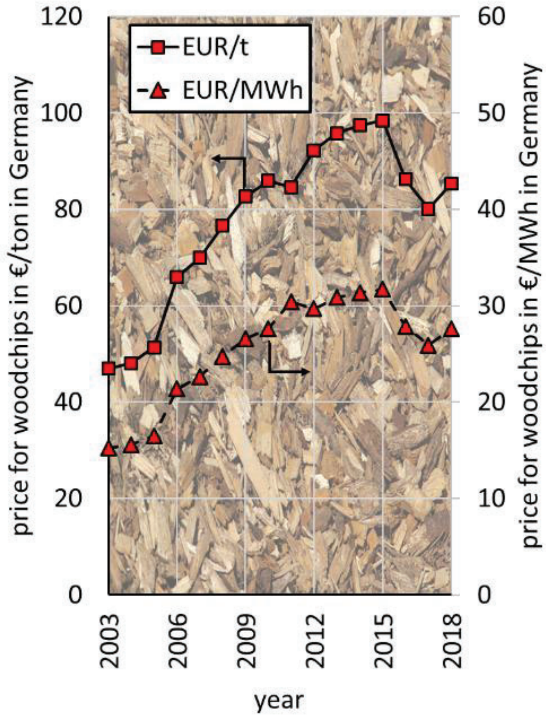

Fig.1: Development of wood chip prices with 35 wt.-% water content in Germany between 2003 and 2018 [4]

Considerations on the DFB steam gasification process showed, that the fuel costs have a significant impact on the economic efficiency [5,6]. Figure 2 was redrawn from estimations on fuel and product prices and relevant efficiencies for their generation to the current situation for DFB steam gasification at industrial scale in 2018 in Austria, presented by Müller and Hofbauer at the Katowice Climate Change Conference [7]. These rough estimations make it obvious, that the use of wood as fuel currently leads to uneconomic operation and fuel flexible operation with low-cost fuels is a key aspect to deal with.

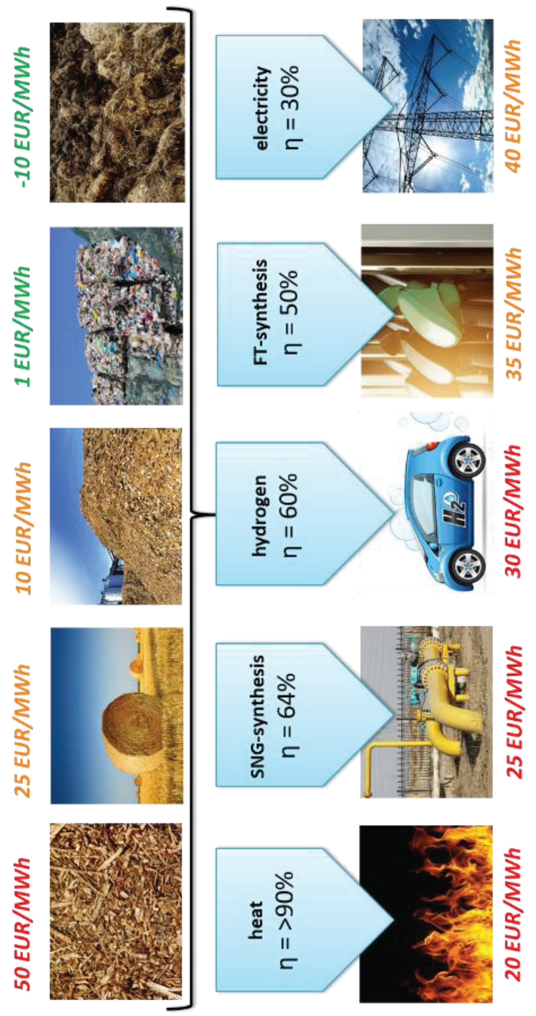

Fig.2: Rough estimation on fuel and product prices for DFB steam gasification

Therefore, during the last years, a main research topic at TU Wien has been the utilization of low-cost residual and waste derived feedstocks. For this reason, a fuel flexible advanced reactor design was developed and constructed with 100 kW fuel power at TU Wien and tested since 2014. An extensive review on the 100 kW pilot plant is given in [8]. On the one hand, utilizing residues and waste fractions as feedstock provides a high potential to produce energy carriers, or commodities in a sustainable, eco-friendly and economic way. On the other hand, these feedstocks often have challenging fuel properties for thermo-chemical conversion processes. Challenges arising with feedstock properties are mainly caused by:

- a high ash content and/or an undesirable ash melting behavior ,
- a high content of volatile matter, or
- other undesired impurities.

Ash-related problems can lead to poor behavior of the fluidized bed itself or to negative effects on downstream equipment. High contents of volatile matter increase the tar content in the product gas, which can lead to tar condensation during cooling of the product gas in heat exchangers. Both effects can result in reduced operating hours and more intensive maintenance efforts. In addition, higher amounts of sulfur, nitrogen and chlorine in the fuel composition may decrease the product gas quality. Although, various feedstock were already tested at 100 kW fuel power, further investigations need to be done to prove or disprove long-term operation stability. For this reason, a scale-up to 1 MW fuel power is suggested to further study the long-term behavior of selected promising feedstock to minimize the risk for further scale-up considerations.
The aim of this study is to provide design data for a basic engineering and to calculate key indicating parameters of a 1 MW fuel flexible plant.

2. Concept and methodology

The simulation work is based on an intensive literature study, operational data from industrial scale plants [5, 9] and experimental results from the advanced and the classic 100 kW pilot plant [10, 11]. The data are simulated by the use of the process simulation software IPSEpro. Thereby, following fuels were investigated:

- softwood (SW) as standard fuel,
- a waste fuel (WF) with a high share of volatile matter, and
- sewage sludge (SS) as fuel with a high ash content.

The fuel composition as well as test runs at the 100 kW pilot plants are documented in detail in [10, 11]. The use of the simulation software IPSEpro regarding the DFB process and thereby adjusted or calculated performance indicating key figures are explained by Müller et al. [12]. Equation 1 gives the steam-to-fuel ratio (φ_{SF}) and equation 2 the steam-to-carbon ratio (φ_{SC}). Equation 3 gives the product gas yield (PGY), equation 4 the steam-related water conversion (X_{H2O}), and equation 5 the cold gas efficiency (η_{CG}). As no additional fuel is fed into the combustion reactor (CR) the introduction of an overall cold gas efficiency is omitted.

$$\varphi_{SF} = \frac{\dot{m}_{steam,GR} + \dot{m}_{H2O,GR,fuel}}{\dot{m}_{GR,fuel,daf}} \quad (1)$$

$$\varphi_{SC} = \frac{\dot{m}_{steam,GR} + \dot{m}_{H2O,GR,fuel}}{\dot{m}_{C,GR,fuel}} \quad (2)$$

$$PGY = \frac{\dot{V}_{PG}}{\dot{m}_{GR,fuel,daf}} \quad (3)$$

$$X_{H2O} = \frac{\dot{m}_{steam,GR} + \dot{m}_{H2O,GR,fuel} - \dot{m}_{H2O,PG}}{\dot{m}_{steam,GR} + \dot{m}_{H2O,GR,fuel}} \quad (4)$$

$$\eta_{CG} = \frac{\dot{V}_{PG} \times LHV_{PG}}{\dot{m}_{GR,fuel} \times LHV_{GR,fuel}} \cdot 100 \quad (5)$$

In contrast to gasification test runs at the 100 kW pilot plant, the key figures are referenced on the product gas after coarse gas cleaning instead of the outlet of the gasification reactor (GR).

3. Results and discussion

The fuel composition used for simulation is shown in **Table 1**. For softwood, data from fuel analyses from 100 kW test runs [10] were the basis and have been matched with data according to Müller [5] for higher ash, sulfur and nitrogen contents for wood chips instead of pellets. The fuel composition of the waste fraction is a mixture of a shredder light fraction and a municipal solid waste fraction from [10]. The composition of sewage sludge is from [11]. During this study, chlorine was not considered and the remaining species were equalized to 100 wt.-%$_{db}$.

Figure 3 shows the process flow diagram, which was the basis for the calculations of the DFB gasification system with coarse gas cleaning, redrawn and modified from [5,9]. The applied fuel is dried to 20 wt.-% water content and fed into the gasification reactor, where it is gasified with steam. The water content before drying of softwood and the waste fraction was set to 40 wt.-% and to 65 wt.-% for sewage sludge according to mechanical dewatering.

Tab.1: Fuel composition for simulation

parameter	unit	SW	WF	SS
Water (H_2O)	wt.-%	40 (20)	40 (20)	65 (20)
Ash	wt.-%$_{db}$	1.0	10.1	41.5
Carbon (C)	wt.-%$_{db}$	50.7	71.5	29.7
Hydrogen (H)	wt.-%$_{db}$	5.9	10.7	3.7
Oxygen (O)	wt.-%$_{db}$	42.2	7.0	20.2
Nitrogen (N)	wt.-%$_{db}$	0.2	0.49	3.9
Sulfur (S)	wt.-%$_{db}$	0.01	0.15	1.0
Chlorine (Cl)	wt.-%$_{db}$	n.c.	n.c.	n.c.
LHV*	MJ/kg	14.4	26.9	9.1

* based on 20 wt.-% water content as fed into GR calculated with IPSEpro, n.c.: not considered

The exiting product gas is led through a separator with 80% particle separation efficiency. Downstream the PG is cooled and cleaned with a fabric baghouse filter for particle removal at 180°C with a particle separation efficiency of 99.9%. In the fabric filter, also a tar reduction of 30% was approximated according to measured data from Wolfesberger [13]. After that, a scrubber operated at 40°C with rapeseed methyl ester (RME) as solvent cleans the product gas of its major tar content. The tar separation efficiency was estimated with 80% and no particles are present in the gas exiting the scrubber. Within the scrubber, also 50% of NH_3 is separated. Further gas cleaning is not considered within this study.

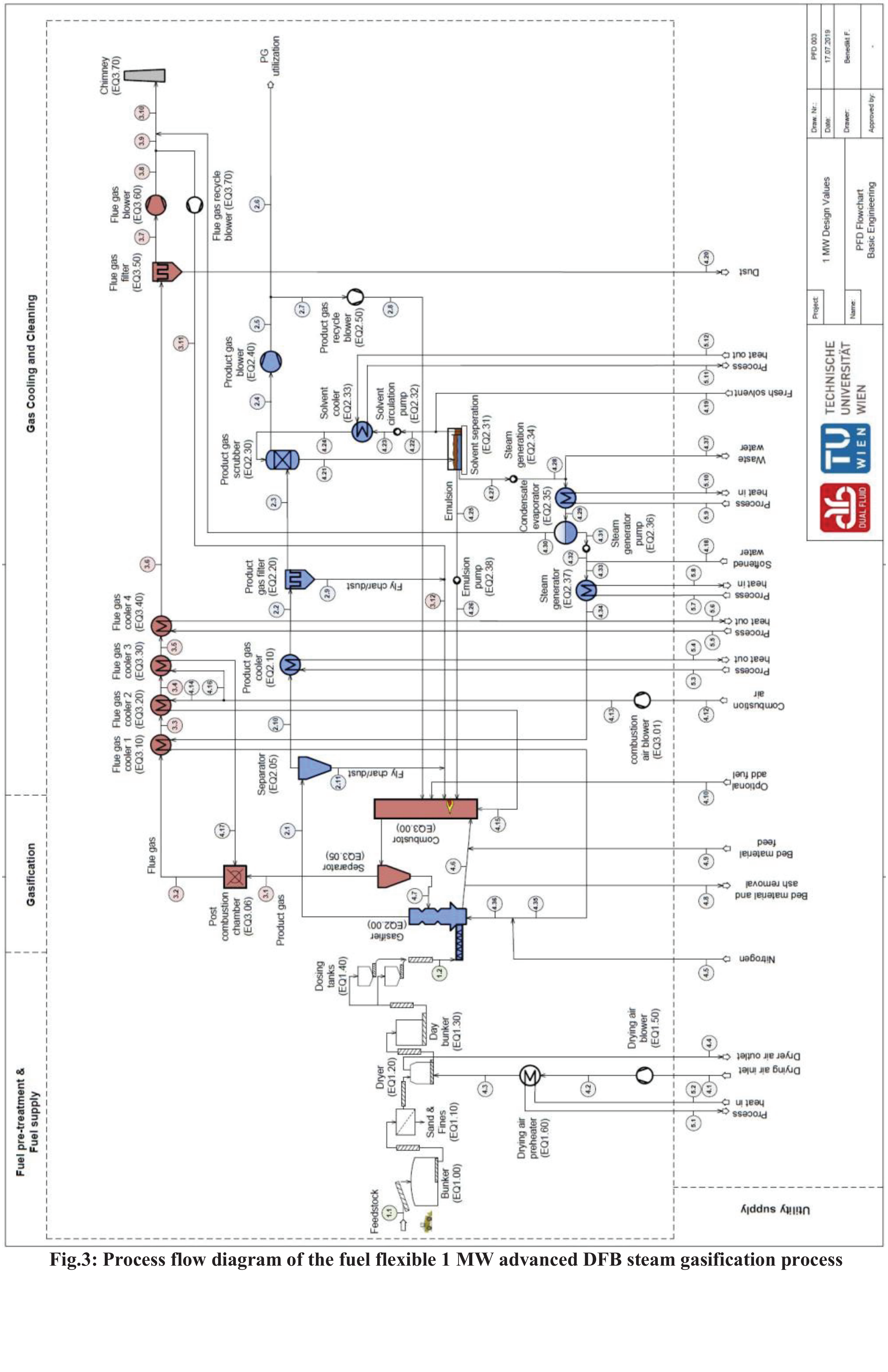

Fig.3: Process flow diagram of the fuel flexible 1 MW advanced DFB steam gasification process

The RME saturated with tar is converted as additional fuel in the combustion reactor. 10% of the evaporated water is removed via the flue gas and the rest is used as gasification agent after steam generation and internal superheating within the flue gas line to 400°C. In addition, the combustion air for the combustion reactor and the post combustion chamber is heated by heat exchangers from the flue gas to 400°C.

Tab.2: Operation parameters

parameter	unit	SW	WF	SS
GR temp.	°C	800	800	800
CR temp.	°C	950	950	950
fuel to GR	MW	1.0	1.0	1.0
fuel to GR	kg/h	249	134	396
fuel to CR	MW	0.0	0.0	0.0
heat losses*	%	5	5	5
fresh RME	kg/h	2	2	2
fresh bed material	kg/h	5	5	5
nitrogen**	Nm^3/h	5	5	5
φ_{SF}	kg/ kg_{daf}	0.55	1.20	1.0
φ_{SC}	kg/kg	1.07	1.51	1.97
air ratio λ in CR	kg/kg	1.25	1.25	1.25

*based on fuel input into GR,
**nitrogen used for purging of the fuel hopper system and PG filter

Tab.3: Product gas composition and impurities after the gasification reactor

	unit	SW	WF	SS
H_2O	vol.-%	28.8	34.1	51.1
H_2	vol.-$\%_{db}$	46.3	46.6	39.1
CO	vol.-$\%_{db}$	21.0	12.5	16.5
CO_2	vol.-$\%_{db}$	21.1	14.7	20.9
CH_4	vol.-$\%_{db}$	8.8	19.2	7.9
C_2H_4	vol.-$\%_{db}$	0.50	3.1	2.4
C_2H_6	vol.-$\%_{db}$	0.05	0.35	0.09
C_3H_8	vol.-$\%_{db}$	0.0	0.0	0.56
N_2	vol.-$\%_{db}$	2.2	3.1	4.1
H_2S	ppm_v	58	684	11540
NH_3	ppm_v	475	4375	73913
tar	g/Nm^3	5	100	5
char	g/Nm^3	20	20	20
dust	g/Nm^3	20	100	300

The outlet temperatures of process heat from flue gas cooler 4 and the product gas cooler are set to a difference of 10°C to the entering flue gas or product gas, respectively. The flue gas from the combustion reactor is fed to a post combustion chamber to ensure complete combustion and then cooled to 150°C prior to the flue gas filter. Particles removed by the flue gas filter exit the system. The main operation parameters and input values applied for calculation of the 1 MW plant are shown in Table 2.

Table 3 shows the product gas composition, which was calculated via IPSEpro and impurities of the PG: tar, fly char and dust, which are set values. High amounts of sulfur and nitrogen in the fuel led to a low product gas quality with high amounts of ammonia and hydrogen sulfide. Table 4 shows the performance indicating key figures, which were calculated with IPSEpro.

Tab.4: Performance indicating key figures

parameter	unit	SW	WF	SS
PGY	Nm^3_{db} $/kg_{waf}$	1.2	1.7	1.0
X_{H2O}	kg_{H2O}/kg_{H2O}	0.29	0.41	0.13
η_{CG}	%	73.4	70.8	63.3

Figure 4 shows the energy flow diagram based on the lower heating value for the gasification of 1 MW softwood with 20 wt.% water content and coarse gas cleaning calculated by IPSEpro and compiled with the software e!Sankey pro. The continuous addition of fresh rapeseed methyl ester (RME) of 2 kg/h, which accounts for 20.5 kW of chemical energy flow, is depicted as additional fuel input. Besides, the steam input is from an external source with 44.7 kW. Thereby, a product gas with 734.4 kW of chemical energy and 93 kW of thermal energy was calculated. Downstream of the coarse gas cleaning 2.5 kW of chemical energy are present in the tar within the PG. After internal steam superheating and pre-heating of the combustion air to 400°C, 101.3 kW of heat are left over within the flue gas cooler 4 (cf. **Figure 3**) at 657°C. The product gas cooler can provide 92.7 kW of heat at 790°C. Thus, an internal steam generation could be provided and 149.6 kW of thermal energy flow would still be available. For the drying of the feedstock from 40 wt.-% to 20 wt.-%, 59.3 kW of heat flow would be needed for water evaporation, which is not depicted within **Figure 4**. For this, also a part of the low temperature heat from the solvent cooler at 55°C with 59.1 kW could be used. However, at state-of-the-art combined heat and power plants with the DFB process the low-temperature heat from solvent cooling is not utilized. Losses of chemical and thermal energy derived from the DFB reactor system, flue gas leaving the plant at 150°C, ash and bed material attrition, ammonia and waste water account for 74.8 kW.

Figure 5 & 6 show the energy flow diagrams for the use of waste fraction and sewage sludge, respectively.

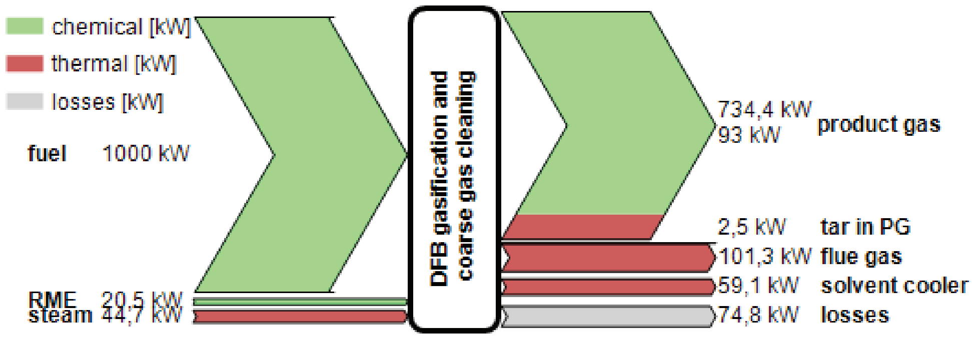

Fig.4: Energy flow diagram 1 MW softwood

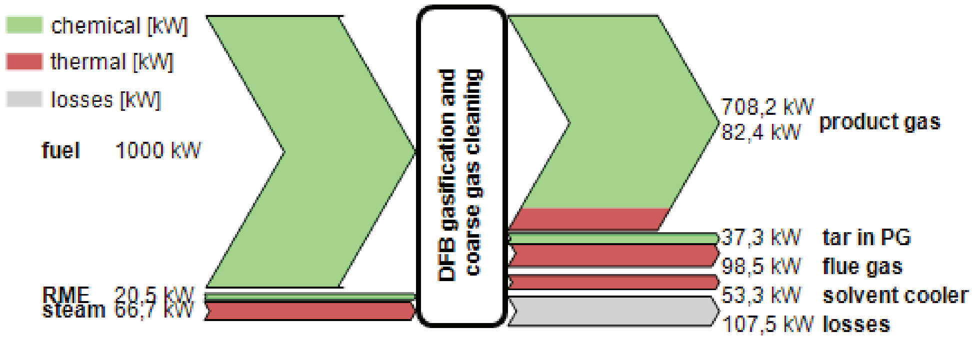

Fig.5: Energy flow diagram 1 MW waste fraction

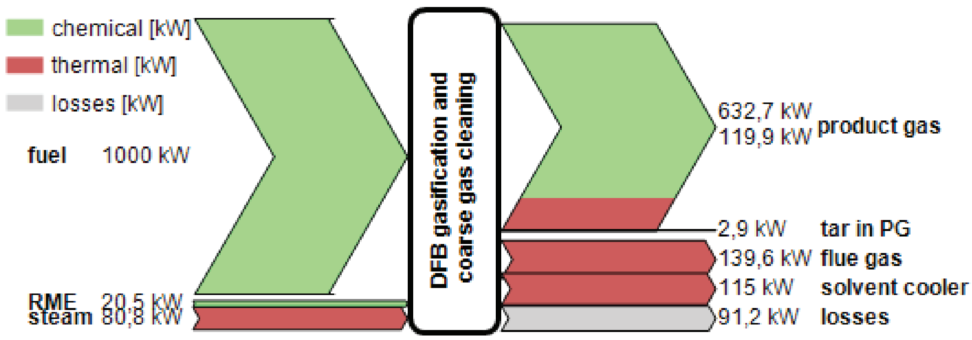

Fig.6: Energy flow diagram 1 MW sewage sludge

Due to higher amounts of steam necessary for the more challenging fuels, increased energy inputs for steam production are needed. However, also for these fuels, an internal steam generation would be feasible. The higher tar yield in the PG for the gasification of the waste fraction is obvious.

The amount of energy flow for drying, which is not presented within the figure was calculated with 31.8 kW for the waste fraction and 350.1 kW for the sewage sludge. As for the waste fraction, an internal utilization of thermal energy for drying is applicable, for the sewage sludge an external heat source or a partly utilization of the product gas needs to be applied.

4. Summary, Conclusion and Outlook

DFB systems were used for energy conversion technologies to supply electricity and heat or synthetic natural gas at industrial scale between 8-32 MW fuel input power. However, most plants suffered from difficult economic conditions due to the increasing fuel prices for woody biomass over the last decades and static green feed-in tariffs. Therefore, the investigation of fuels with low prices was a major focus over the last years at TU Wien. However, some fuels have challenging properties for thermochemical conversion. While test runs for several hours at a 100 kW fuel input scale did not lead to operational problems, it is difficult to make reliable statements on long-term operation for some of the investigated fuels. Therefore, a scale-up to 1 MW fuel input is suggested to minimize the risk for further scale-up considerations.

Experimental data and extensive knowledge of process simulation offered the basis for this study to provide the data for the gasification of 1 MW softwood as standard fuel, a waste fraction as fuel with a high volatile matter content and sewage sludge as fuel with a high ash content. With the use of process simulation, mass- and energy balances were calculated and performance indicating key figures are presented. Hence, design data for a basic engineering of an advanced fuel flexible 1 MW DFB steam gasification plant including coarse gas cleaning are presented. An extensive gas cleaning for other synthesis routes is not part of this study but should be investigated in the future.

Abbreviations

CR	combustion reactor
daf	dry and ash-free
db	dry basis
DFB	dual fluidized bed
GR	gasification reactor
IPSEpro	equation-oriented process simulation software
$LHV_{GR,fuel}$	lower heating value of fuel to GR (kJ/kg)
LHV_{PG}	lower heating value of dry and char- and tar-free PG (kJ/Nm^3_{db})
$\dot{m}_{GR,fuel}$	mass flow of fuel to GR (kg/s)
$\dot{m}_{C,GR,fuel}$	mass flow of carbon in fuel to GR (kg/s)
$\dot{m}_{GR,fuel,daf}$	mass flow of dry and ash-free fuel to GR (kg_{daf}/s)
$\dot{m}_{H2O,GR,fuel}$	mass flow of water in fuel to GR (kg/s)
$\dot{m}_{H2O,PG}$	mass flow of water in PG (kg/s)
$\dot{m}_{steam,GR}$	mass flow of steam to GR (kg/s)
PG	product gas
PGY	product gas yield ($Nm^3_{db}/kg_{fuel,daf}$)
ppm_v	parts per million by volume
$\dot{Q}_{loss}$	radiative heat losses (kW)
RME	rapeseed methyl ester, bio-diesel
SS	sewage sludge
SW	softwood
TU Wien	Vienna University of Technology
vol.-$\%_{db}$	percent by volume on dry basis
vol.-%	percent by volume
$\dot{V}_{PG}$	dry volumetric product gas flow (Nm^3_{db}/s)
wt.-%	percent by weight, percent by mass
X_{H_2O}	steam-related water conversion (kg_{H2O}/kg_{H2O})
η_{CG}	cold gas efficiency (%)
λ	air–fuel equivalence ratio (kg/kg)
φ_{SC}	steam to carbon ratio (kg_{H2O}/kg_C)
φ_{SF}	steam to fuel ratio ($kg_{H2O}/kg_{fuel,daf}$)

5. Acknowledgements

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6. References

[1] J. Karl, T. Pröll. Steam gasification of biomass in dual fluidized bed gasifiers: A review. Renewable and Sustainable Energy Reviews. **98** (2018) p64-78

[2] R. Rauch, J. Hrbek, H. Hofbauer. Biomass gasification for synthesis gas production and application oft he syngas. Wiley Interdisciplinary Reviews: Energy and Environment. **3** (2013) p343–62

[3] M. Kuba, H. Hofbauer. Experimental parametric study on product gas and tar composition in dual fluid bed gasification of woody biomass. Biomass and Bioenergy. **115** (2018) p35-44

[4] www.carmen-ev.de/infothek/preisindizes/hackschnitzel/jahresmittelwerte accessed on 10.07.2019

[5] S. Müller. Hydrogen from Biomass for Industry - Industrial Application of Hydrogen Production Based on Dual Fluid Gasification. Doctoral thesis, TU Wien (2013)

[6] J. Corella, J.M. Toledo, G. Molina. A review on dual fluidized-bed biomass gasifiers. Ind. Eng. Chem. Res. **46** (2007) p. 6831–9

[7] S. Müller, H. Hofbauer. Thermochemical conversion of biomass residues to green fuels , electricity and heat. COP24, Katowice: (2018) p. 15.

[8] J.C. Schmid, F. Benedikt, J. Fuchs, A.M. Mauerhofer, S. Müller, H. Hofbauer. Syngas for biorefineries from thermochemical gasification of lignocellulosic fuels and residues - 5 years' experience with an advanced dual fluidized bed gasifier design. Biomass Conversion and Biorefinery, first online: 16 August 2019, https://doi.org/10.1007/s13399-019-00486-2

[9] V. Wilk, H. Hofbauer. Analysis of optimization potential in commercial biomass gasification plants using process simulation. Fuel Processing Technology **141** (2016) p.138-47

[10] F. Benedikt, J.C. Schmid, J. Fuchs, A.M. Mauerhofer, S. Müller, H. Hofbauer. Fuel flexible gasification with an advanced 100 kW dual fluidized bed steam gasification pilot plant. Energy **164** (2018) p. 329-43

[11] J.C. Schmid, U. Wolfesberger, S. Koppatz, C. Pfeifer, H. Hofbauer. Variation of feedstock in a dual fluidized bed steam gasifier—influence on product gas, tar content, and composition. Environmental Progress & Sustainable Energy **31** (2012) p. 205-15

[12] S. Müller, J. Fuchs, J.C. Schmid, F. Benedikt, H. Hofbauer. Experimental Development of Sorption Enhanced Reforming by the Use of an Advanced Gasification Test Plant. International Journal of Hydrogen Energy **42** (2017), p. 29694-707

[13] U. Wolfesberger. Profiling tar behavior in dual fluidized bed biomass steam gasification. Doctoral thesis, TU Wien (2013)