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BIOMASS GASIFICATION COMBINED CYCLE THERMODYNAMIC OPTIMISATION USING INTEGRATED DRYING

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ABSTRACT

The conversion of solid fuels such as biomass into a combustible gas provides the opportunity to enhance the efficiency of biomass based power systems. It allows solid fuels to be used in high efficiency power generation processes such as **I**ntegrated **G**asification **C**ombined **C**ycle (IGCC). Using woody biomass with high water content without drying has negative effects on the overall efficiency of the process. The option of using dryer biomass is limited by the higher fuel costs. Drying with low temperature heat is the link between the usage of wet low price fuel and optimum process conditions.

In this paper, the possibilities of integrating fuel drying into a pressurized IGCC process and the effects on the efficiencies are discussed. For this purpose, an equation oriented process simulation environment with a modular structure is used. Different dryer types are integrated into this tool. Several solutions for the implementation of a drying into an IGCC process are investigated using steam and exhaust gas as heat sources. The obtained results are analyzed by the means of an exergetic analysis. Finally an optimum concept with a high electrical efficiency was obtained which will also meet the environmental regulations.

Integrating drying into a biomass based IGGC concept can be an essential step for the economic operation of a plant.

Keyword: biomass, gasification, IGCC, drying

INTRODUCTION

During recent years, the interest on biomass utilization for power generation has increased since it has significant environmental benefits. It is a renewable energy resource that is CO_2 neutral and provides low SO_2 emissions, being a positive contribution to limit the greenhouse effect. Currently 14 % of the total world energy consumption is covered by biomass [1].

However, there is even a much bigger potential to produce, for instance, at least 50 % of Europe's total energy requirement on the basis of biomass fuels [2]. The technologies for the primary thermal conversion of biomass for electricity production are combustion, gasification, and pyrolysis. An overview of existing technologies is given by Bain et al. [1]. Gasification combined with a gas engine or gas turbine has the advantage of having a higher electric efficiency and will in the future achieve lower electricity production costs than direct combustion [2]. Kwant [3,4] give an overview of principles and practice of biomass gasification.

Fluidized-bed gasifiers provide excellent mixing and gas/solid contact, causing high reaction rates and conversion efficiencies. Further, there is the possibility of addition of catalysts to the bed material to influence the product gas composition and reduce its tar content [5]. Since the gasification reactions are endothermic, the process must be supplied with energy. This can be done by partial combustion of the biomass within the gasifier using a hypostoichiometric amount of air as gasification agent. Air gasification produces a gas with low heating value (around 4-7 MJ/m^3, lower heating value (lhv)); gasification with pure oxygen, produces a high quality gas (around 10-18 MJ/m^3, lhv), requires, however, additional costs for oxygen production. A gas of similar quality can be produced by using a dual fluidized-bed-system. The gasification zone is fluidized with steam, yielding a nitrogen free gas with a lhv around 12-14 MJ/m^3. The necessary heat in the gasification reactor is supplied by hot circulating bed material [6]. The latter is heated up in a second fluidized bed reactor by combustion of residual char. In this study only autothermic air gasification is looked at.

Two power plants based on biomass IGCC concepts have been built during the last decade. The first one, Vaernamo [7,8] located in Sweden, is a pressurized IGCC, with a separated fuel preparation and drying plant. The second one was ARBRE [9], located in UK. It was an atmospheric based IGCC; sadly the ARBE project failed due to financial problems.

In this work possibilities of integrating the drying of biomass into pressurized IGCC concepts are investigated. Several solutions for the implementation are looked at using steam and exhaust gas as heat sources. Theses concepts are evaluated in terms of their exergetic performance and discussed in detail.

NOMENCLATURE

CFB	circulating fluidized bed	
DLL	Dynamic Link Library	
e	specific exergy of a stream	$J \cdot kg^{-1}$
E_{0i}	molar standard exergy of species i	$J \cdot mol^{-1}$
h	specific enthalpy of a stream	$J \cdot kg^{-1}$
IGCC	integrated gasification combined cycle	
LHV	molar lower heating value	$J \cdot mol^{-1}$
lhv	specific lower heating value	$J \cdot kg^{-1}$
$\dot{m}$	specific mass flow	$kg\ s^{-1}$
M	mean molar mass of a stream	$kg \cdot mol^{-1}$
MDK	model developer kit	
PSE	process simulation environment	
P_{el}	electric power	W
R	general gas constant (R = 8.31451)	$J \cdot mol^{-1} \cdot K^{-1}$
s	specific entropy of a stream	$J \cdot kg^{-1} \cdot K^{-1}$
T	temperature	K
wf	water free	
wt	weight	
y_i	molar fraction of species i	$mol \cdot mol^{-1}$

Greek symbols:

Δp	pressure drop of equipment	
η	energetic efficiency	1

Subscripts:

cons	consumption
chem.	chemical
el	electric
Fuel	fuel (biomass)
gross	gross value
GT	gas turbine
m	mechanic
net	net value
PG	product gas
Q, q	heat
s	isentropic
ST	steam turbine
0	ambient conditions

SIMULATION TOOL

Calculations are performed in an equation oriented process simulation environment (IPSEpro®) with a modular structure to offer flexible handling of unit operations. This process simulation tool solves the modeled process by forming a non-linear equation system, which is solved by a Newton-Raphson-algorithm. An essential advantage of this tool is the modular set up, shown in Fig. 1.

The process simulation environment (PSE) with the equation solver (Kernel) refers to a model library, with the information about the utilized apparatus. This model library can be edited with a special editor called model developer kit (MDK), which allows the implementation of user-defined models. The thermodynamic and physical data for the calculations are provided by external property libraries (DLLs). The standard software package IPSEpro®, which is designed to model standard power plant processes, has been greatly enlarged to model and describe gasification processes; Dryers, gasifiers and gas cleaning equipment have been implemented, by mass- and energy balances, including possible chemical reactions and empiric correlations from measurements of real gasification plants [10].

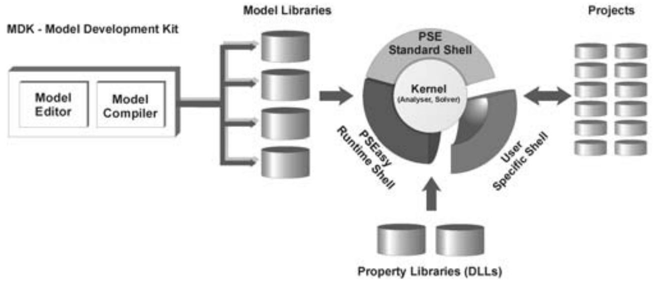

Fig. 1 Structure of the simulation environment

Conventionally the performance of a process is described in terms of the energetic performance, referred to lower heating value of the fuel and sensible heat. This evaluation method has the disadvantage to neglect the convertibility of theses energy forms.

A possibility to include this into the calculation is to introduce the exergy, the part of the energy which can be transformed into all forms of energy. This offers the possibility to investigate processes in terms of its exergetic behavior and efficiency.

The exergy of a stream consists of the exergy of heat and chemical exergy [11].

$$e = e_q + e_{chem} \tag{1}$$

For ideal gas mixtures, the specific exergy is defined by:

$$e_q = h - h_0 - T_0 \cdot [s - s_0] \tag{2}$$

$$e_{chem} = M^{-1} \cdot \left[\sum_i (y_i \cdot E_{0i}) + R \cdot T_0 \cdot \sum_i (y_i \cdot \ln y_i) \right] \tag{3}$$

The exergy of the enthalpy in Eq. (2) can be calculated as a function of the enthalpy *h*, entropy *s* and the ambient conditions (index *0*) and is a property of the gas mixture. The thermal environment defined for the present study is 298.15 K, 1.0 bar. For the calculation of the chemical exergy the molar exergy of pure substances [11] based on an equilibrium environment by Diederichsen et al. [12] is used. The standard exergy of chemical compounds can be calculated from element exergy and standard free enthalpy [11]. For pure water and steam the exergy is defined using IAPWS-IF97 [13] data, for solid mixtures it is expressed in analogy to ideal gases, neglecting the pressure dependency. For organic mixtures the chemical exergy is set equal to the higher heating value [14].

DISCRIPTION OF THE PROCESS

The process is based on a large pressurized IGCC concept with an electrical power output of 20 MW, using biomass with water content of 40 % as fuel feedstock.

The basic outline of the plant is a pressurized gasification with hot gas conditioning, coupled with a double stage steam cycle in condensation mode. Fig. 2 shows the flow diagram.

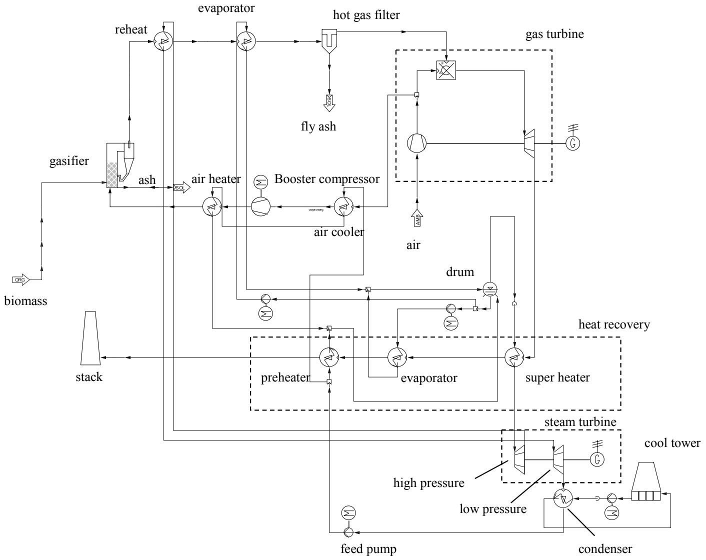

Fig. 2 Flow diagram of the IGCC process

Biomass is pressurized and enters the **C**irculating **F**luidized **B**ed (CFB) reactor with 21 bar. Air is used as gasification agent, which is extracted as a side stream from the gas turbine (about 10% of the mass flow), cooled in an evaporator, pressurized and reheated again to 250 °C. The additional pressurization is necessary to cover the pressure drops which occur in the gasifier and the gas conditioning until the combustion chamber of the gas turbine. The product gas is cooled, firstly with a reheat to about 700 °C and secondly with an evaporator to 400 °C before it is dedusted in a hot gas filter. The fly ash of the filter has high carbon content, and is therefore recycled into the gasification reactor.

In the combustion chamber of the gas turbine the cleaned product gas is combusted with the remaining air of the gas turbine compressor and leaves the turbine at about 470 °C. The gas is further cooled in the heat recovery, with a superheater, an evaporator and a feed water preheat, before released to the atmosphere at 120 °C. The steam cycle consists of a two-stage turbine (84 bar/18 bar). Heat for the steam cycle is obtained from the product and the flue gas.

For the evaluation of the process three characteristic efficiencies are defined:

The gross electrical efficiency is calculated as the fraction of the produced electrical power referred to the fuel power before the dryer.

$$\eta_{gross} = \frac{P_{elGT} + P_{elST}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{4}$$

The net electrical efficiency is calculated as the fraction of the produced electrical power reduced by the electrical consumption by the apparatus referred to the fuel power before the dryer.

$$\eta_{net} = \frac{P_{elGT} + P_{elST} - P_{elCons}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{5}$$

The chemical efficiency refers to the amount of chemical energy which can be transferred from the biomass into the product gas:

$$\eta_{chem} = \frac{\dot{m}_{PG} \cdot lhv_{PG}}{\dot{m}_{Fuel} \cdot lhv_{Fuel}} \tag{6}$$

SIMULATION OF THE PROCESS

The simulation of the process is based on the ambient conditions and the general set-up given in Table 1.

Table 1
Ambient conditions and general set-up

Ambient conditions	
temperature	15 °C
relative humidity	60 %
ambient pressure	1.013 bar
General set-up	
stack temperature	120 °C
high pressure steam	84 bar / 450 °C
low pressure steam	18 bar / 450 °C
condenser conditions	80 mbar / 41.5 °C
Δp heat exchangers (PG-, flue gas-, air side)	10 mbar
Δp evaporators steam side	0.1 bar
Δp pre-heater steam side	3 bar
Δp reheat steam side	2 bar
Δp super heater steam side	0.1 bar

The implemented efficiencies for the specific apparatus can be found in Table 2.

Table 2
Efficiencies of the specific apparatus

	η_s	η_m
high pressure turbine	0.84	0.99
low pressure turbine	0.82	0.99
compressors	0.75	0.99
pumps	0.75	0.99
gas turbine	0.88	0.985
compressor gas turbine	0.85	0.985
	η_{el}	η_m
motors, generators	0.98	0.98

As fuel biomass with the following feedstock characteristics is used, given in Table 3.

Table 3
Biomass feedstock characteristics

ash wf	3.0	[wt%]
C wf	47.6	[wt%]
H wf	6.2	[wt%]
O wf	42.9	[wt%]
N wf	0.293	[wt%]
S wf	0.031	[wt%]
Cl wf	0.013	[wt%]
water content	40	[wt%]
lhv wf	17760	[kJ/kg]
lhv	9680	[kJ/kg]

INFLUNCE OF THE BIOMASS WATER CONTENT

In the following the influence of the water content on the process shall be discussed.

Fig. 3 shows the effect of the variation of the water contents from 40 to 10 %, when the total power output of the plant is kept constant. It can be clearly seen, that the reduction of the water content from 40 % to 10 % results in an increase in the net electrical efficiency of over 2.5 %. Furthermore, the strong effect on the chemical efficiency of the gasifier can be seen; an increase of 20 % can be obtained if the water content is reduced to the above mentioned values.

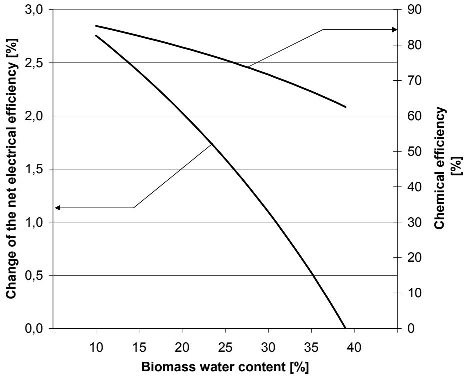

Fig. 3 Influence of the biomass water content

In Fig. 4 the influence of different biomass water contents on the exergy losses of different apparatus at constant total power output of 20 MW electrical is given.

The greatest sensitivity can be seen for the gasifier, where the water in the fuel has to be evaporated. The heat for the evaporation has to be produced by partial combustion of the fuel, which has a strong influence on the exergy loss, due to the irreversibility of the combustion. The necessary additional combustion dilutes the product gas with inert combustion gases and additional nitrogen from the gasification air. This results in a reduction of the lower heating value and thereby the exergy flow of the product gas. Wet fuel reduces the power of the gas turbine due to the lower heating value of the product gas. This results also in a decline of the exergy losses in the gas turbine. In total it can be concluded that in terms of electrical efficiency as well as in terms of exergy losses the use of dry wood gives considerable advantages. For the further simulations a biomass water content after the dryer of 15 wt% is assumed.

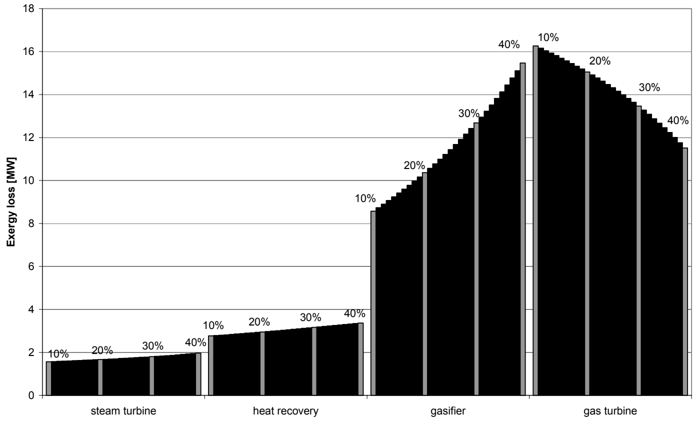

Fig. 4: Exergy losses of different apparatus at different biomass water contents (10% - 40%, marked by gray lines)

DRYING OF BIOMASS

If biomass is dried the water content is reduced, though according to the drying temperature organic emissions occur [15-17]. In the temperature range from 80 - 120 °C according to Rupar [18] oak shows a carbon loss of 0.04 – 0.08 %. If superheated steam is used (3 bar, 133 °C) according to Münster [19] a loss in the lower heating value of 1.2 %, corresponding to an average carbon loss of 1 % using wood as a fuel, occurs. With an increase in the drying temperature from 190 °C to 350 °C a rise in the carbon loss from 1 % to 10 % for pine wood and up to 17 % for birch wood has been measured [20].

It can be easily seen that the carbon loss at low drying temperatures (<120 °C) can be nearly neglected. To investigate the influence of the carbon loss on the electrical and chemical efficiencies of the process the loss was varied from 0 to 8 %, which can be seen in Fig. 5. Up to a carbon loss of 1 % the influence on the electrical efficiency is rather low (0.4 %), but even small carbon losses can cause undesired gaseous emissions. If only particle removal is installed, the temperature in the dryer should be kept below 100 °C.

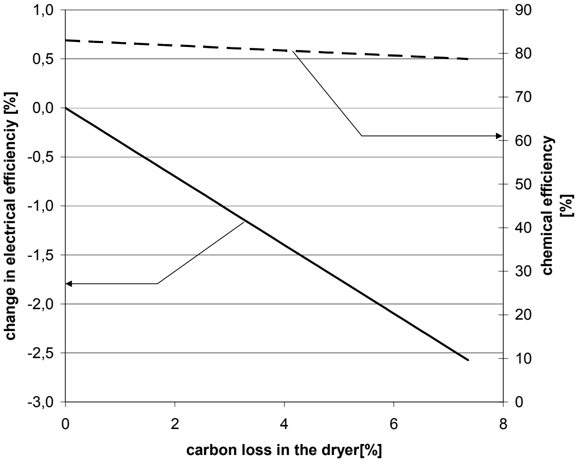

Fig. 5 Influence of the carbon loss in the dryer

Drying of biomass for gasification is until today not a state of the art technology. The applicable drying techniques can be separated into systems with direct and indirect heat transfer.

Using direct drying, rotary drum dryers have been successfully utilized; a warm gas stream (flue gas, heated up air) is fed counter currently to the biomass into the drum. The rotary drum itself provides the transport and mixing of the biomass.

Another type of dryer suitable for low temperature direct drying is the conveyor and the vibro dryer. The conveyor dryer uses a porous belt, which carries the biomass over the cross flow feed of warm gas; the vibro dryer uses a porous metal surface, which is vibrating for better fuel mixing. Warm gas is fed again in cross flow to the biomass through the porous metal surface.

Indirect heat transfer drying techniques transfer the necessary heat indirectly through heat exchangers into the drying equipment; therefore the released drying gases can be separately drawn off. For fast drying of beet slices a pressurized fluidized bed dryer, with internal steam recirculation is often used. This dryer has been successful applied on the drying of biomass wood chips too [20]. A more detailed description will follow at the relevant concept discussion.

RESULTS AND DISCUSSION

In the following, three concepts with integrated drying will be analyzed and evaluated and compared in terms of their efficiencies and their exergy.

Process concept with flue gas drying

For low temperature drying of biomass, especially wood chips, the rotary drum dryers, the conveyor dryer and the vibro dryer are suitable types. This concept is shown in Fig. 6.

The process is equal as the one described above, though the dryer is added. The flue gas after the preheater is mixed with recycled gas from the dryer outlet to reduce the energy demand of the dryer and to adjust the dryer inlet temperature. The necessary heat for the drying is drawn from the product gas. This raises the necessary temperature after the preheater and therefore has a negative effect on the power output of the steam cycle.

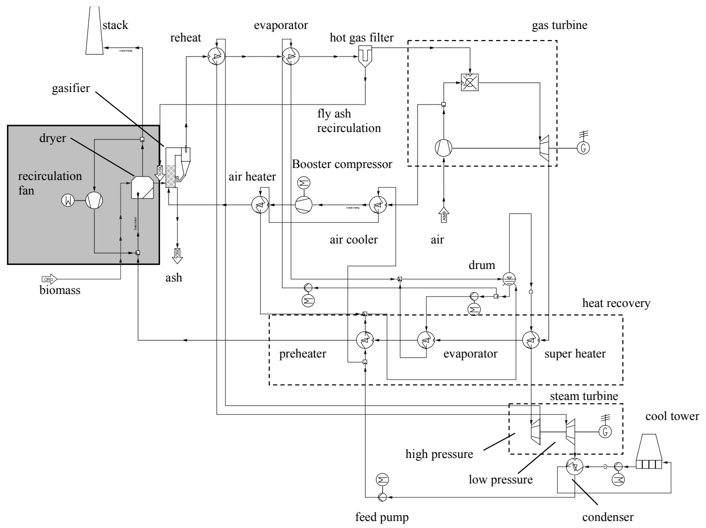

Fig. 6 Flow diagram - flue gas drying

Fig. 7 shows the effect of different biomass water contents on the power output of the steam and gas turbine and the electrical efficiency, respectively. The total net electric efficiency declines with higher water contents as does the power output of the gas turbine, whereas the power output of the steam turbine increases due to the lower dryer heat demand and the higher volume flow through the heat recovery.

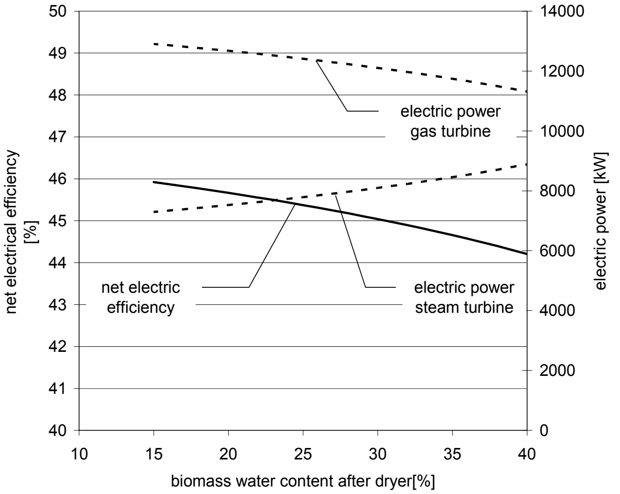

Fig. 7 Influence of different water contents

The theoretical potential for improvement of a certain process unit can be quantified by its exergy loss, though there are avoidable and unavoidable exergy losses. In the gasifier for instance, an avoidable exergy loss would be the heat loss, which can be reduced through further insulation of the gasifier. The irreversibility of the thermo chemical conversion of the biomass is an example for an unavoidable exergy loss.

An evaluation of the exergy losses can be used for the optimization of the process if the avoidable exergy losses are compared with the related cost of their possible improvement. As an example Fig. 8 shows the relative exergy losses of different units and streams of the process referred to the total fuel exergy input.

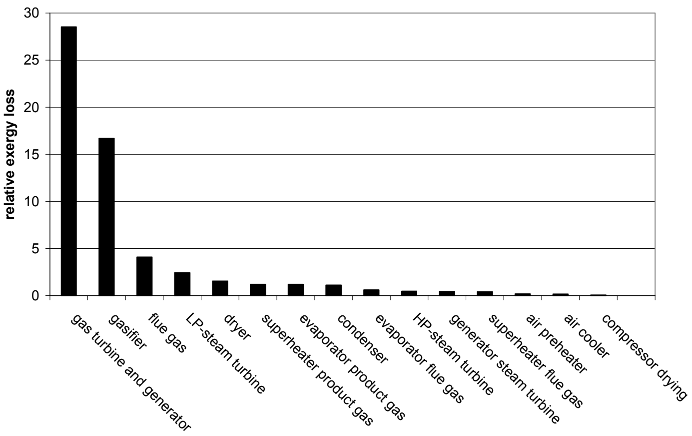

Fig. 8 Relative exergy losses of different units and streams referred to the total fuel exergy input

The highest exergy losses in the described process occur in the gas turbine and the gasifier, mainly due to the irreversibility of the combustion. These could only be reduced if different means of conversion are used, for instance a fuel cell instead of a gas turbine. Further optimization potential can be seen in the flue gas outlet temperature and the quality of the steam turbine.

Fig. 9 shows the exergy flows of the total process, with the exergy of the streams calculated according Eqs. (1)-(3), whereby electricity is considered as pure exergy.

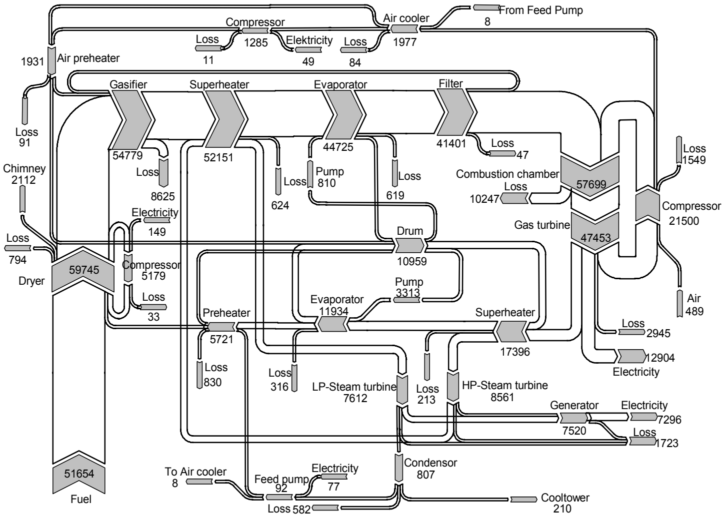

Fig. 9 Sankey-diagramm of the exergy flows – flue gas drying concept

Process concept with air drying

A further reduction of the organic emissions can be achieved using ambient air (15 °C), heated up by flue gas. This gives the advantage, that the dryer can be operated at temperatures below 100 °C. The flue gas of the dryer is partially recycled to reduce the necessary heat demand. This concept is shown in Fig. 10.

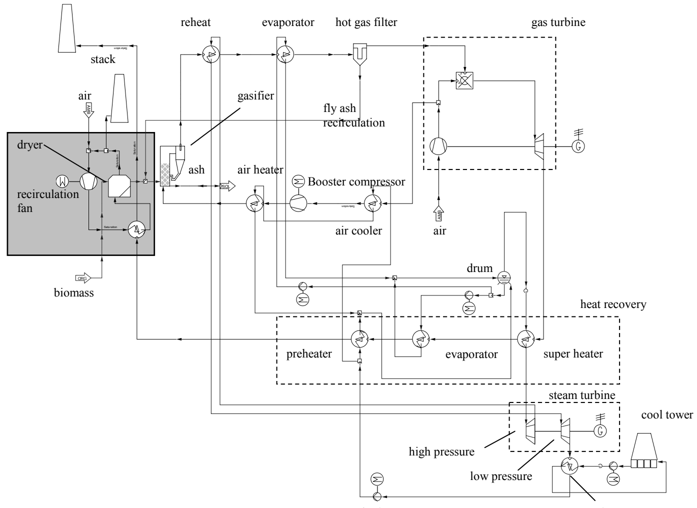

Fig. 10 Flow diagram – air drying

Fig. 11 shows the effect of different biomass water contents on the power output of the steam and gas turbine and the electrical efficiency, respectively. The total net electric efficiency shows a lower sensitivity towards different biomass water contents as in the flue gas drying concept (Fig. 7).

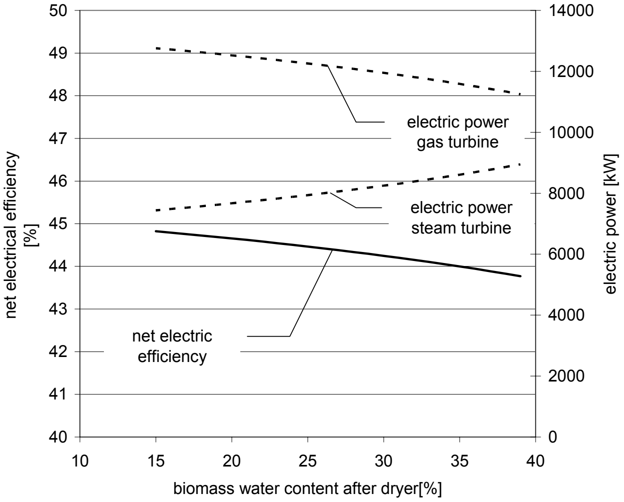

Fig. 11 Influence of different water contents

Process concept with steam drying

Finally, a concept using medium pressure steam as heat source shall be looked at. A description of a fluidized bed steam dryer is given by Jensen [21]. The dryer uses partly the recirculated steam from the biomass to fluidize the chopped wood. The heat for the drying is drawn from steam, extracted after the high pressure steam turbine from the process. The steam is condensed in an internal heat exchanger and the recirculated steam heated up. The steam leaving the dryer is condensed; the yielded heat is fed back into the steam circle. The wastewater from the condenser has to be treated, because it contains organic compounds. The flow diagram with the integration of the fluidized bed dryer can be found in Fig. 12.

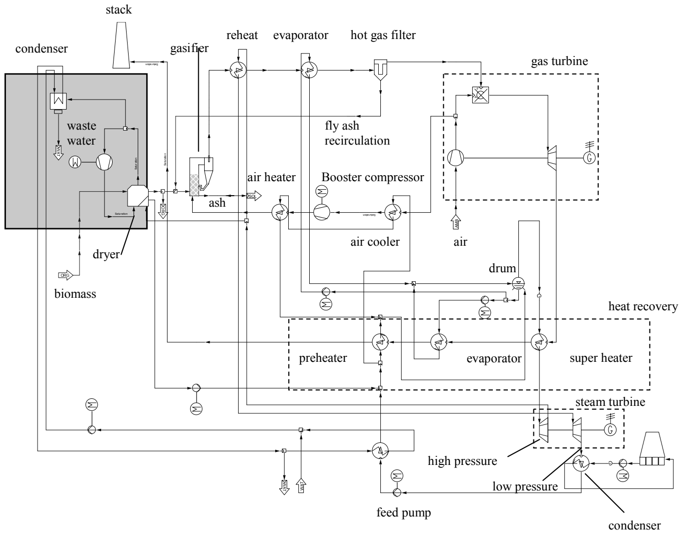

Fig. 12 Flow diagram – steam drying

Fig. 13 shows again the effect of different biomass water contents on the power output of the steam and gas turbine and the electrical efficiency, respectively.

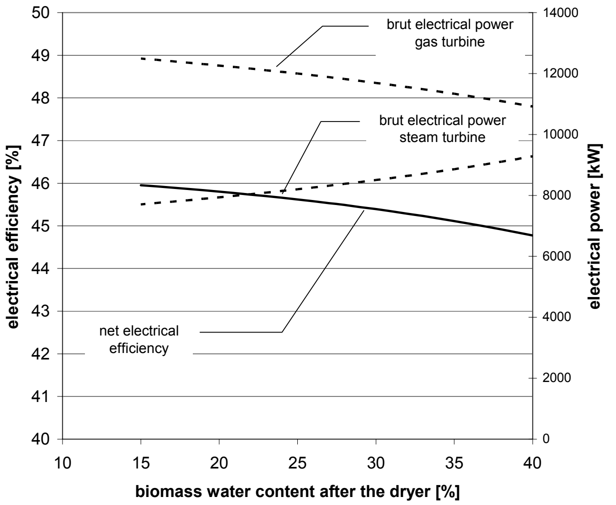

Fig. 13 Influence of different water contents

COMPARISON OF THE CONCEPTS

Fig. 14 gives a comparison of the different concepts in terms of their electrical efficiencies.

It can be seen, that steam drying achieves the highest net electrical efficiency and shows a low own consumption of electricity. In a real plant this little benefit in electrical efficiency (0.1 %) compared to the flue gas drying concept has to be set into relation to the costs for the wastewater treatment.

Using air as drying media the net electrical efficiency is 1.2 % lower as if steam is used, because of the higher flue gas recirculation rate the compressor power increases the own electrical consumption of this concept. Organic emissions can be largely avoided due to the low drying temperature of the wood, so the loss in efficiency may be compensated by the lower post treatment cost of the dyer exhaust.

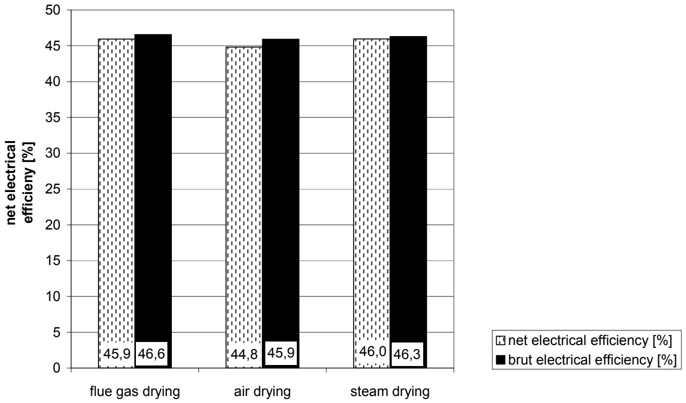

Fig. 14 Comparison of the efficiencies of the different concepts

To operate the dryer using flue gases directly gives equal results in efficiency (45.9 %) as the steam concept, with the advantage, that no waste water is produced.

Interestingly the three concepts show also a different sensitivity, if the water content of the biomass is varied. Steam drying shows a lower sensitivity, equal to air drying than flue gas drying (Fig. 15).

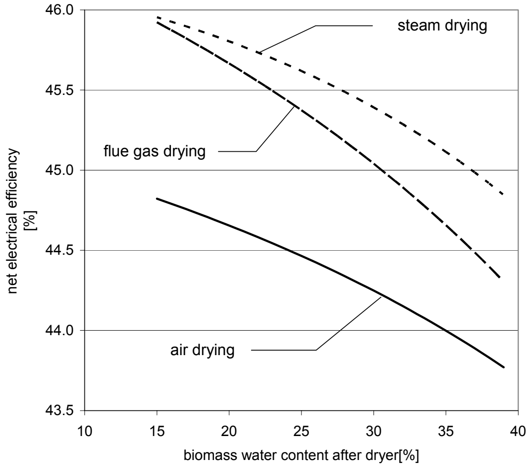

Fig. 15 Sensitivities on the efficiencies of the concepts on a variation of different water contents

Comparing the exergy losses of the three different concepts at constant power output of 20 MW electrical, (Fig. 16) it can be seen that using the steam drying concept the exergy losses in the gas turbine and the gasifier can be reduced whereas the losses raise strongly in the dryer. This can be explained by the higher temperature gradient between the biomass and the steam as well as with the carbon losses in the steam dryer. Because the overall power output is kept constant the reintegration of the heat yielded from the condenser after the dryer has a positive effect on the exergy losses in the gasifier and the gas turbine. The two concepts based on the heat from the flue gas show only minor differences in their exergy losses.

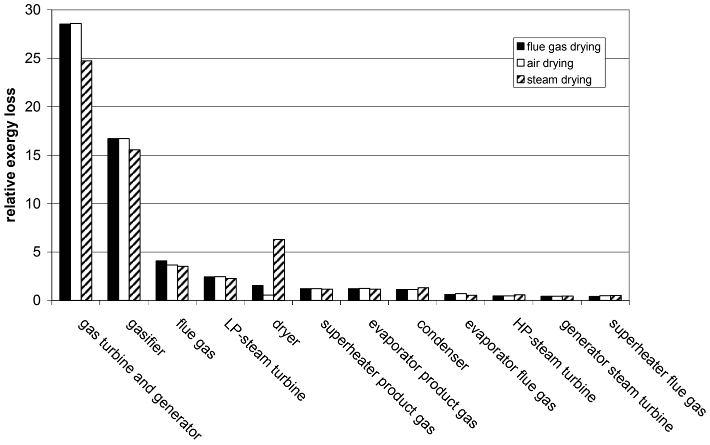

Fig. 16 Comparison of the exergy losses

In the following, the exergy inputs into the dryer shall be investigated. The exergy input is defined as the exergy necessary to dry the fuel to the desired water content. This exergy is provided at the concept of the flue gas drying and the air drying by hot flue gas after the economizer and at the steam drying concept by steam drawn from the steam cycle. A comparison of the exergy inputs can be found in Fig. 17.

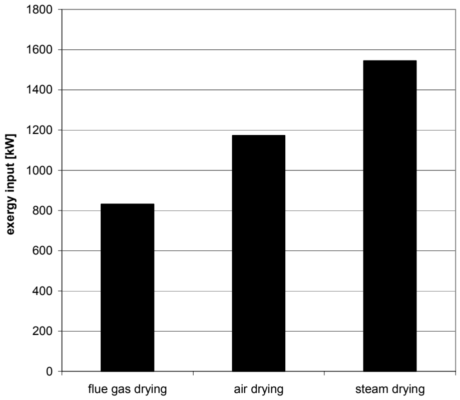

Fig. 17 Comparison of the exergy inputs in the dryer

The dryer in the flue gas concept needs the lowest exergetic input. This means it uses less valuable energy. The larger exergetic input in the air drying concepts is mainly because ambient air has to be heated up which needs more energy than using hot flue gas. Drying the biomass using steam as heat source requires the largest exergetic input, due to the fact that steam (20 bar, 280 °C) has still a high exergetic value and therefore is in terms of energy more valuable than hot flue gas at 180 °C.

The detailed exergetic losses in the dryer are given in Fig. 18. Steam as drying media shows the largest exergetic losses, including the carbon losses of 5 % in the dyer exhaust gas. Due to the lower temperature difference and the lower carbon loss, the exergetic loss in the flue gas drying concept is considerable lower, reaching the minimum if heated ambient air is used.

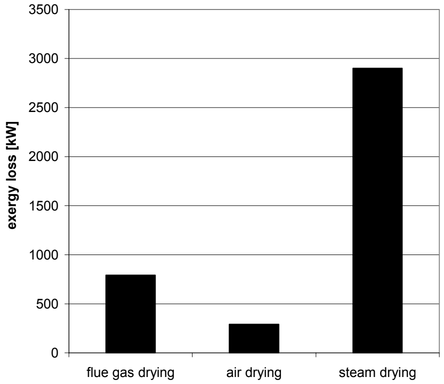

Fig. 18 Comparison of the exergy losses in the dryer

CONCLUSION

The reduction of the biomass water content can contribute significantly to the electrical efficiency of the biomass based IGCC process. Improvements of 2.5 % in electrical efficiency referred to the fuel power can be achieved if wood with a water content of 15 % instead of 40 % is used. Using low temperature heat from the flue gas for the drying process gives the significant advantage of a low exergetic input into the dryer as well as low organic emissions. Furthermore the waste water formation is avoided. This concept can achieve net electrical efficiencies of up to 46 % which is high for biomass options and offers the best compromise between efficiency and residual treatment.

For future biomass based IGGC plants the integration of the fuel drying into the total concept is a proper method to increase the fuel flexibility and offers the advantage to operate the plant at optimum conditions.

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REFERENCES

[1] Bain, R. L., Overend, R. P. and Craig, K. R., 1998, “Biomass-fired power generation,” Fuel Process. Technol., 54, pp. 1-16.
[2] Bridgewater, A. V., 1995, “The technical and economical feasibility of biomass gasification for power generation,” Fuel, 74, pp. 631-653.
[3] Kwant, K. W., 2001, "Status of Gasification in countries participating in the IEA Bioenergy gasification activity," IEA Bioenergy Gasification Country Reports, pp. 1-66.
[4] Kwant, K. W., 2002, “Status of Gasification in Countries participating in the IEA biomass gasification and GASNET activity,” Novem, Utrecht, pp. 1-118.
[5] US Department of Energy, 1992, “Electricity from biomass – a development strategy,”, Report No. DOE/CH10093-152.
[6] Hofbauer, H., Rauch, R., Loeffler, G., Kaiser, S., Fercher, E., and Tremmel, H., 2002, “Six Years Experience with the FICFB-Gasification Process”, Proc., 12th European Biomass Conference, W. Palz et al., eds., ETA, Florence, Italy, pp. 982-985.
[7] Stahl, K., 1998, "Värnamo Demonstration Plant - Construction and commissioning," Skogs Sätteri AB and Skogs Boktryckeri AB, Sydkraft, Trelleborg.
[8] Stahl, K., 2001, "Värnamo Demonstration - The Demonstration Program," Skogs Sätteri AB and Skogs Boktryckeri AB, Sydkraft, Trelleborg.
[9] Pitcher, K., Paterson, B., Weekes, A., Neergaard, M., Ståhl, K. and Jensen, A. S., 1996, “Progress achieved in BIGCC projects and prospects for the future,” Proc. 12th European Conference for Energy from Biomass, Industry and Climate Protection, Amsterdam, The Netherlands, pp. 71-77.
[10] Kaiser, S., 2001, “Simulation und Modellierung von KWK-Verfahren auf Basis Biomassevergasung”, Ph.D. thesis, Vienna University of Technology, Austria.
[11] Baehr, H.D, 2000, Thermodynamik, Springer, Berlin.
[12] Diederichsen, Ch., 1991, “Referenzumgebungen zur Berechnung der chemischen Exergie”, Fortschritt-Ber. VDI, Reihe 19, Nr. 50, VDI-Verlag, Duesseldorf, Germany.
[13] The International Association for the Properties of Water and Steam, 1997, “Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam”, Erlangen, Germany.

[14] Baehr, H.D., 1979, “Die Exergie der Brennstoffe”, Brennst.-Waerme-Kraft, 31, pp. 292-297.

[15] Brammer, J. G. and Bridgwater, A. V. 2001, "Study of biomass gasifier-engine systems with integrated drying for combined heat and power.," Progress in Thermochemical Biomass Conversion, 5th, Tyrol, Austria, Sept. 17-22, 2000, pp.307-321. .

[16] Brammer, J. G. and Bridgwater, A. V., 1999, "Drying in a biomass gasification plant for power or cogeneration," Proc. of the Biomass Conference of the 4th Americas, Oakland, Calif., pp.281-287.

[17] Wahlund, B., Yan, J. and Westermark, M., 2002, "A total energy system of fuel upgrading by drying biomass feedstock for cogeneration," Biomass and Bioenergy, **23**, pp. 271-281.

[18] Rupar, K. and Sanati, M., 2003, "The release of organic compounds during biomass drying depends upon the feedstock and/or altering drying heating medium.," Biomass and Bioenergy, 25, pp. 615-622.

[19] Münster, M., 1996, “Use of dried biomass in BORAS,” Proc., 9th European Bioenergy Conference, Copenhagen, Denmark, pp. 923-928.

[20] Fagernäs, L. and Sipilä, K., 1992, “Emissions of Biomass Drying,” Development in thermochemical conversion, A. V. Bridgewater et al., eds., Chapman&Hall, pp. 783-793.

[21] Jensen, A. S., 1996, “Pressurized steam drying of biofuel,” Proc. 9th European Bioenergy Conference, Copenhagen, Denmark, pp. 937-941.