

Studies of biomass fuelled MCFC systems

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Abstract

In the present work, the methods, techniques and results obtained during the studies of biomass fuelled molten carbonate fuel cell (MCFC) systems within the Swedish national fuel cell program are presented. The power plants are 60 MW class, utilising biomass (i.e. wood chips) as the primary fuel. The biomass is converted via pressurised gasification into a gaseous form that, after subsequent cleaning, can be used in the fuel cells. An investigation of the effects of gasification pressure, temperature and the influence of internal reforming on the overall system performance is presented.

All studies were carried out using the Aspen Plus™ with Model Manager™ simulation package. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Biomass; Gasification; System study; Molten carbonate fuel cell (MCFC); System analysis

1. Introduction

As the oil crisis hit the western world in 1973, it became evident how vulnerable an energy system relying on a single source of primary energy can be. This fact, together with the predictions of some sources that the oil and natural gas resources would only last for some 40 and 60 years [1] led to an increased interest for developing energy conversion processes based on other sources of primary energy. The estimated number of years that oil and natural gas will be available is, however, debatable since the available statistics do not cover all the countries producing these fuels.

The first primary fuel source chosen for development was coal, partly because it has a predicted availability of more than 200 years [1], and partly because of an already existing knowledge of coal utilisation as a fuel or for upgrading into more valuable products. As a result of these efforts, several large scale integrated gasification combined cycle (IGCC) power plants have been built both in Europe [2–6], and in USA [7,8]. The basis in the systems is that coal is gasified, cleaned and utilised as a fuel in a power generation system combining both gas and steam turbines. At the same time some countries, such as Sweden and Finland, without any resources of coal or oil, choose to start a similar development of gasification processes, now using biomass, i.e. wood

chips, as the primary source of energy [9]. As a result of these activities, both designs and construction of several biomass-based systems deploying IGCC technique for power generation have been developed [10–14]. The objective of the present work is a system analysis of a biomass-powered IGCC system where electricity is generated by molten carbonate fuel cell stacks, that is an IGCC–MCFC system. The commercial software Aspen Plus™ has been used and the modelling of the fuel cells and the gasifier by using this software is especially discussed.

2. Gasification

Gasification is the term often used to describe the thermo-chemical processes that take place between a solid fuel and a gaseous reacting media, like air, oxygen or steam in order to produce a combustible gas or synthesis gas rich in carbon monoxide and hydrogen. The difference compared to combustion is that the amount of oxidant, i.e. oxygen in air or pure oxygen or steam, is not high enough to enable complete oxidation, i.e. combustion. Instead, a partial oxidation, i.e. gasification, will take place. The overall gasification process can be divided into four steps, resulting in a product mixture of gaseous, liquid and solid products.

The first step is drying, where the moisture of the fuel fed to the gasifier, coal or biomass, evaporates. The second step where volatile compounds in the fuel evaporate is called

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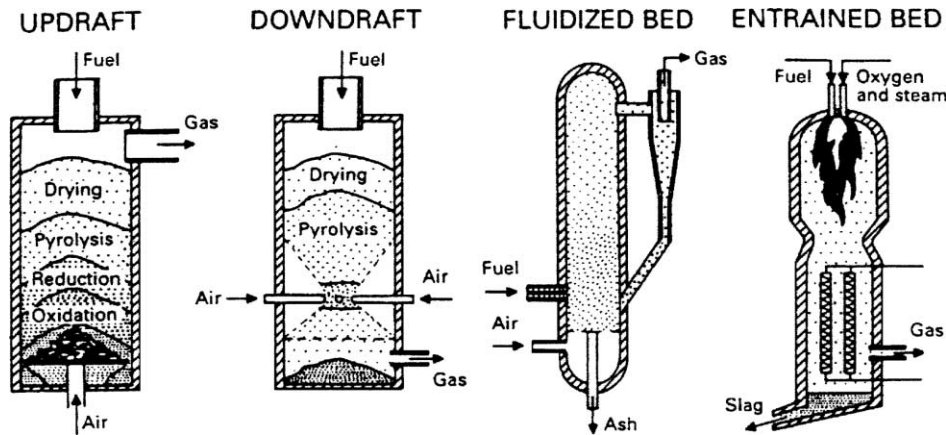


Fig. 1. Different gasifier concepts [15,47].

devolatilisation. This is followed by pyrolysis, the step where the major part of the carbon content of the fuel is converted into gaseous compounds in the reduction zone of the gasifier. The result of the pyrolysis is, apart from gases, a carbon rich solid residue called char. In the last step, called gasification, the char is partly oxidised into gaseous products and partly burnt to generate the heat needed for the overall gasification process. Even though the reactions taking place during gasification are not very complicated and complex themselves, the difficult part is to establish the kinetic relations between the different species.

A few of the reactions taking place during the different steps of gasification are (here illustrated for coal):



2.1. Biomass gasifiers

As the quest for new energy conversion routes took off in the 1970s, the advantages of an initial biomass gasification step was realised. The development route chosen by many was to develop biomass gasifiers by modifying different types of existing coal gasifiers so that they could use biomass instead of coal as their primary fuel. The scale of the overall system mostly decides the choice of which gasifier type to use, fixed bed, entrained bed or fluidised bed. As a rule, fixed

bed gasifiers, shown in Fig. 1, are generally used for small scale operation with gas engines [15], having an electrical output of about 80–500 kW [16,17].

The main difference between the updraft and downdraft fixed bed gasifiers is that in the first case, the product gas passes the pyrolysis and drying zone of the fixed bed on its way out, resulting in a product gas with higher contents of tars and higher hydrocarbons than for the downdraft gasifier, where the product gas passes through the hot zone where the tars and higher hydrocarbons are decomposed. The entrained bed gasifier has found less use for biomass gasification, mainly because of the problems coupled to the pulverising of the biomass to be fed entrained with air [15]. If, however, one wants to build larger systems, the only realistic gasifier concept with a high enough biomass throughput for electricity production in the multi-MW size is the fluidised bed gasifier [15–17], schematically shown in Fig. 1.

2.2. Choice of gasification pressure and media

All the gasifier types can be operated at either an atmospheric or elevated pressure. The advantage with pressurised operation is generally considered to be that with increasing pressure, the gasifier and other process equipment can be made smaller in size. The advantage of atmospheric gasification, on the other hand, is that less energy is consumed by gas compression. When it comes to the choice of gasification media, there are two options, air or oxygen. Normally, the only reason for selecting oxygen is whether the produced gas is intended for synthesis gas or pipeline distribution [17], otherwise it has been found to be unsuitable from both an economical, as well as an energetical point of view [16–19].

Economic and energetical reasons are not, however, the only ones for using air as the gasification media for fluidised bed gasifiers operating with biomass. In order to operate the gasifier properly, a high enough gas flow is needed to accomplish fluidisation. If this were to be done with oxygen, steam would have to be used to dilute the oxygen, otherwise

the result would simply be combustion of the biomass [20]. As the heat of vaporisation for water is high, the generation of steam would require the use of process heat that could be used for power generation elsewhere in the system. Since air comes with a “built-in” dilutant, i.e. nitrogen, it has become the primary choice as biomass gasification media.

2.3. Fuel cells and gasification

The idea of combining a gasification process with a fuel cell is far from new, and can be seen as an attempt to bring the coal gasification-based systems up to a higher efficiency level. Several studies about this have been carried out, only to mention a few [21–30]. Consequently, it is not at all surprising that the biomass gasification-based powerplants would follow a similar route. One of the first suggestions of combining biomass gasifiers and fuel cells into an energy production system was brought forward in the late 1970s [31], but it is only recently that the fuel cell-biomass gasification combination has reached a somewhat more widespread interest [32–38].

The work presented here deals with a study of a biomass gasifier MCFC combination (IGCC–MCFC), investigating how such factors as gasification temperature and pressure together with or without internal reforming in the fuel cells influence the performance of the overall system.

3. Models used within the study

In the following section, the more significant models used in the study are described. These models are the gasifier model and the fuel cell model.

3.1. The gasifier model used in the study

When a biomass gasifier is to be modelled for system studies, there are at least two approaches that can be taken. The first one would be to build a detailed mathematical model using mass and energy balances of the entire gasifier, based on the reactions taking place, their specific reaction rates, the heat of reaction for each reaction as well as the thermal constraints of the gasifier materials itself. It comes without saying that this model would soon become very complex, and cumbersome to use. Especially, the establishment of all the reaction kinetics and mechanisms for the reactions taking place in the system would be a major obstacle to overcome [20,39,40].

As a consequence, the mathematical modelling of biomass gasifiers according to the first approach will include a high degree of empirical knowledge in addition to the complex mathematical relations guiding the process of gasification. Several models exist, often stemming from coal gasification models. Some of these models are referred to as the contact time distribution models, the two-region models and the hydrodynamic flow models. And this is only for one

type of fluidised bed gasifier, the bubbling bed reactor [41,42]. The other, more systems oriented approach, would be to collect data from existing gasifiers, and use as a basis for a gasifier model that consists of simple correlation equations for yield.

As the study of a MCFC system fuelled by a biomass gasifier was initiated, the choice had to be made if a detailed and complex gasifier model, according to the first approach, was to be used in the study; or if a less complex model, according to the second approach, would suffice. We found that if the first route had been selected, the study would have transferred from a biomass IGCC–MCFC study into a task of biomass gasification model development. The method that the authors found to be the most suitable in this case was to adopt a simple yield model to describe the gasifier based on the yield reactor module in Aspen PlusTM [43].

The advantage of a yield model in this particular case is that the mass- or molar-yield per unit mass of feed to the model is known, i.e. there is no need to worry about knowing all the actual reactions taking place within the reacting system itself. This technique is also the one that is often used when modelling coal gasifiers. The consequence is, however, that one has to have data from either an existing gasifier, or the output from an already developed complex model.

3.2. Validation of the yield model against the complex model

The performance of the gasifier in this study was supposed to match that of a gasifier, which was used in a study performed by Vattenfall Utveckling AB [44]. This gasifier model is only characterised by a certain set of input, as well as corresponding output values: the algorithms forming the model were, however, not available to us. The solution to this problem in the present study was to use another model, the yield model, and via correlation's adaptation to the set of input and output values presented in the Vattenfall study. The input values, used by Vattenfall for their model, specify a certain percentage of sulphur and nitrogen in the biomass feed.

The output values from the Vattenfall model do not, however, include the contaminant level compounds like H₂S, COS, NH₃ and HCN formed from the sulphur and nitrogen in the biomass, although Vattenfall do specify conversion of sulphur and nitrogen into the contaminant compounds. Therefore, two possibilities exist:

1. The hydrogen, oxygen, carbon and nitrogen content of the H₂S, COS, NH₃ and HCN is not part of the specified output stream hydrogen, oxygen, carbon and nitrogen.
2. They are part of the output stream specified content of hydrogen, oxygen, carbon and nitrogen, in the form of the contaminant compounds.

Knowledge about which of these two possibilities that is the actual one, is not available to us.

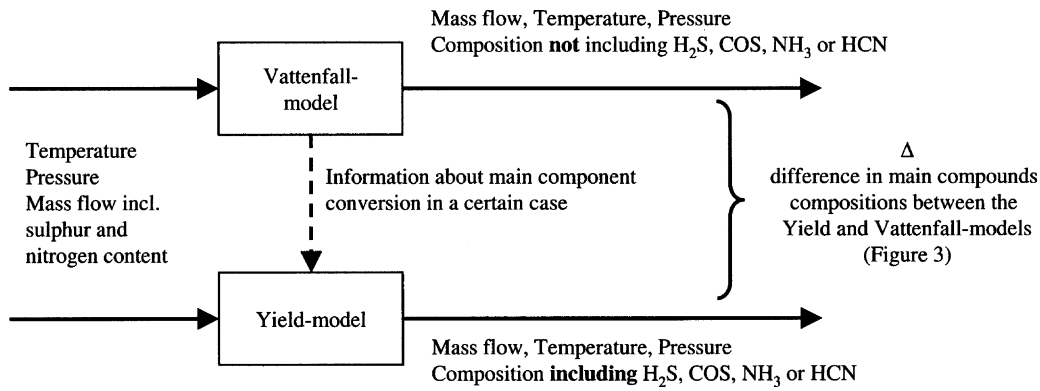


Fig. 2. Relation between the Vattenfall model and the yield model.

In our study, we have chosen to work along the second possibility, and as opposed to the Vattenfall model, do specify the contaminants in the output stream. If our assumption is correct, the two models will not be the same, and their relation would be described by Fig. 2. If the results of our calculations show that the output stream compounds apart from the contaminant compounds are the same for the Vattenfall and yield models, that would imply that the first possibility above would be valid.

However, as can be seen in Fig. 3, there is a difference between the results, which point towards the case according to the second possibility. This makes us confident that our initial assumption, as to which possibility to assume, was correct. An advantage of using the yield model is, that now the gasifier can be included as part of the overall mass and energy balances, and it also allows for a simpler alteration

between the six operational points for the gasifier during simulations.

3.3. The fuel cell model used within the study

The fuel cell model used in the studies is a “one-point-model” in which it uses a constant average cell voltage and a constant average fuel utilisation to calculate the production of the fuel cells according to Faraday’s law (Eq. (10)):

$$P_{el,dc} = \left(\sum n_i y_i \right) U_{fuel} \dot{N}_{anode} FE_{stack} \quad (10)$$

where $P_{el,dc}$ is the electrical power produced by the fuel cell stacks (W), y_i the mole fraction of fuel species i in the anode gas, n_i the number of electrons transferred during the electrochemical conversion of i to carbon dioxide and water

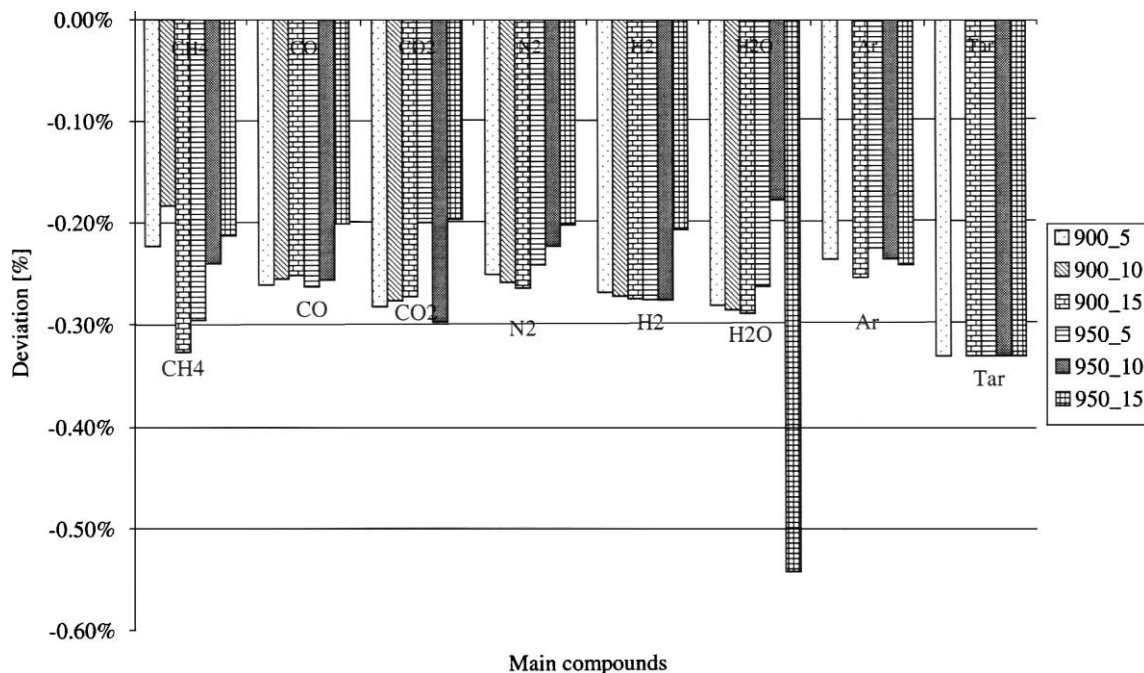


Fig. 3. Deviation between product stream composition as calculated by Vattenfall based on their gasifier model, and the yield model adopting the results from the Vattenfall gasifier model.

(this number equals two for hydrogen and carbon monoxide, and would be eight for direct electrochemical oxidation of methane), U_{fuel} the average fuel utilisation, \dot{N}_{anode} the reactant flow to the anode (kmol/s), F the Faraday's constant (As/kmol), and E_{stack} is the average cell voltage (V). In Eq. (10), CH_4 is included as a fuel only in the case of internal reforming. Otherwise it is treated as an inert. There is no fuel cell model in Aspen PlusTM. However, by combining several models, a set of interconnected blocks was obtained in Aspen PlusTM that could simulate the most important features of the fuel cell stack.

The basic idea for designing this set of blocks is to produce the correct change of state between inlet and outlet streams in the fuel cell stack. This includes ensuring the correct transfer of matter between the anodic and cathodic gas streams, the correct outgoing stream for electrical work, and that the stack is adiabatic and has the correct temperature difference between the outgoing anodic and cathodic gas streams. Furthermore, the outgoing anodic stream should be an equilibrium mixture.

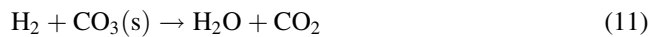
To obtain those features, we utilise the fact that the change of state in the adiabatic cell stack must be uniquely defined by the fuel utilisation and the extracted electrical work if the outlet streams are assumed to have a given temperature difference. Within the outer boundary of the cell stack it then does not matter how the change of state occurs. Therefore, we can substitute the real process with any system that gives the same change of state.

The system of Aspen PlusTM model blocks shown in Fig. 4 has been designed such that each step should be an easily understandable step. The introduction of an invented component, CO_3 , is used to carry out the correct transfer of matter between the anodic and the cathodic side. By assuming that this is a solid having zero standard enthalpy of formation and heat capacity, and very high melting point, it does not affect the energy balances of the steps where it is

involved. This simplifies the reasoning and representation in Aspen PlusTM significantly. The heat stream between the last steps is adjusted to make the temperature difference between the anodic and cathodic gas equal to the given one. The electrical work is extracted from the step denoted as anode.

The anode side of the fuel cell model, Fig. 4, contains four model blocks. The first one is a stoichiometric reactor where the shift reaction is carried out irreversibly to the right. This results in a fuel gas containing only hydrogen as the reacting species. This reasoning is based on a consequence of the first law of thermodynamics often related to as Hess's law, which states that ΔH and ΔU for any chemical reaction is independent of the path. Additional support for this reasoning is also given by the fact that the predominant route for electrochemical conversion of carbon monoxide is via the water-gas shift reaction (4) [45].

In the case of internal reforming of methane, the same reasoning according to Hess's law is applied, and also methane steam reforming Eq. (7) is carried out irreversibly to the right in the first model block. The next anode block is another stoichiometric reactor where the anode reaction:



takes place. It is also from this block that the heat stream representing produced ΔC power is withdrawn. In the third model block there is a check that no $CO_3(s)$ remains in the outlet stream from the anode reactor.

In the last anode-side reactor water-shift equilibrium, and in the case of internal reforming methane steam reforming equilibrium, is re-established at the desired outlet temperature. Any excess heat is transferred to the cathode side. The cathode side is comprised of three model blocks. The first one is a stoichiometric reactor, where the cathode reaction:

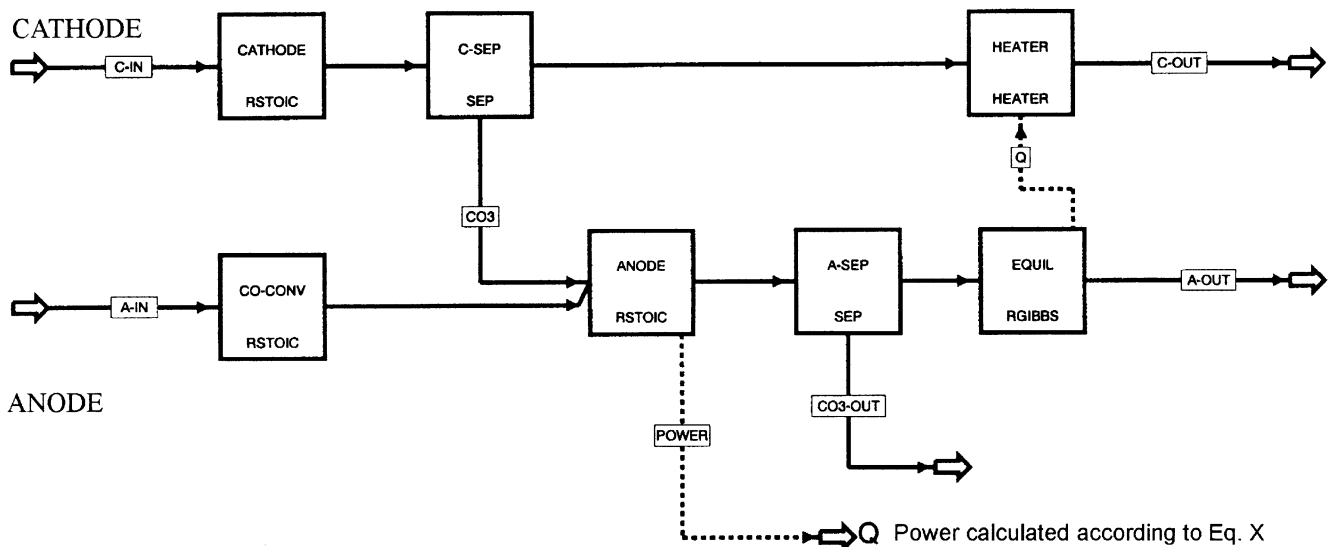


Fig. 4. Schematic drawing of the fuel cell model used.

takes place. The production of CO_3 is guided by the amount of hydrogen that reacts at the anode.

Next is a separator block where CO_3 is removed and transferred to the anode side. Finally, a heater adds the heat transferred from anode to cathode, giving the resulting cathode off-gas temperature.

One of the obvious drawbacks of the fuel cell model is, i.e. does not take operational parameters such as gas composition, pressure and flow into account. For a more detailed and complete study of a biomass IGCC–MCFC system, a more detailed stack model should be used. The only problem is that the models suitable for simulation studies that do exist up to date are only considered with gas compositions found when using either natural gas or gasified coal as a fuel. No models exist that account for the gas compositions resulting from a biomass gasifier.

4. Systems studied

The schematic layout of the biomass IGCC–MCFC power plant used in the simulation is shown in Fig. 5. The primary fuel, biomass, is fed to the biomass dryer where the biomass humidity is reduced from 50 to 15%, and fed via a pressurisation system to the gasifier. In the gasifier biomass and air react forming a gas containing mainly carbon oxides, hydrogen, nitrogen and methane.

The gas leaving the gasifier is cooled before entering the gas cleaning section of the system where the first step is a water wash for removal of ammonia and tar. This is followed by a conventional low temperature sulphur removal step resulting in a gas with less than 1 ppm sulphur. The approach with low temperature purification was chosen, since these processes are well established, whereas high temperature sulphur capture is still undergoing development [20]. The purified gas is re-heated and mixed with steam before entering the anode compartments of the fuel cells for electrochemical conversion.

The resulting anode off-gas is used for the purified gas reheating, as well as for supplying heat to the district heating system. After removal of condensed water, the cooled anode off-gas is fed to a catalytic combustor, where remaining

Table 1
Biomass elementary analysis

Component	Concentration (wt.%)
C	49.0
H	6.0
N	0.5
O	42.0
S	0.04

Table 2
Biomass data

Characteristic parameter	Value
Biomass moisture before drying (%)	50
Biomass moisture after drying (%)	15
Heating value	
LHV (kJ/kg dry biomass)	19200
HHV (kJ/kg dry biomass)	20600
Biomass feed (including 15% moisture) (kg/s)	19.3

Table 3
Input data for the 60 MW biomass system

Parameter	Value
Gasifier	
Type	Air blown, pressurised
Operation pressure (bar)	5, 10 or 15
Gasifier exit temperature ($^{\circ}\text{C}$)	900 or 950
Gasifier cold gas efficiency (%)	~80
Gasifier carbon conversion (%)	99
Fuel cell	
Average cell voltage (mV)	714
Pressure (bar)	4.5
Average temperature ($^{\circ}\text{C}$)	650
Fuel utilisation (%)	70 and 85
Air compressors	
Isentropic efficiency (%)	72
Blowers, compressors and turbines	
Isentropic efficiency (%)	86
Mechanical efficiency (%)	96
Inverter	
Efficiency (%)	96

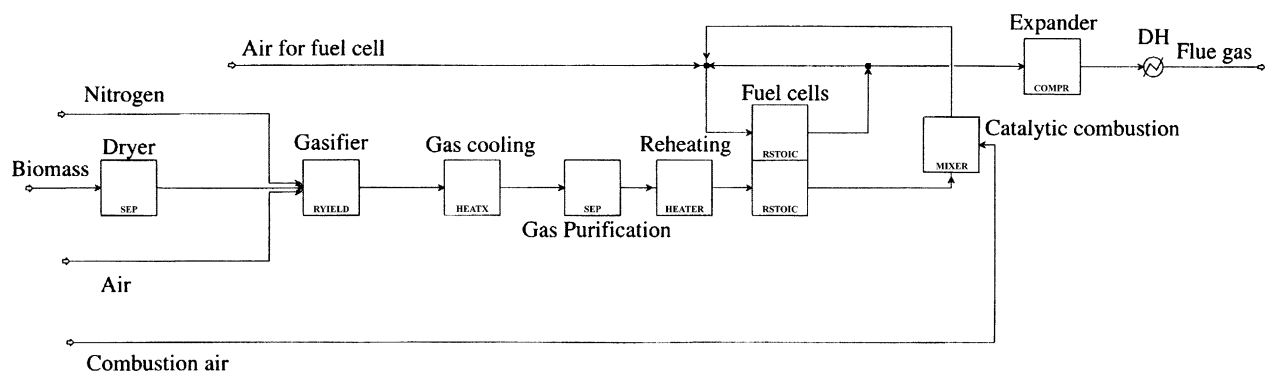


Fig. 5. Schematic flowsheet of the 40 MW biomass fuelled MCFC system.

combustibles are consumed. The resulting gas is mixed with fresh air and the cathode exhaust recycled from the cathode outlet, and fed to the fuel cell cathodes.

Part of the cathode off-gas leaving the fuel cells is recycled back to the cathode inlet. The other part is passed to an expansion turbine for subsequent power generation. The expanded gas is used for steam production and district heating. Steam generated at various parts of the system is used for power generation in steam turbines and the resulting

low-pressure steam is utilised in the biomass dryer. Some of the most important input data used in the biomass study are shown in Tables 1–3.

5. Results of the simulations

In the presented study, the gasifier pressure was varied between the three discrete levels of 5, 10 and 15 bar.

Table 4
Results of the 60 MW simulations with 70 and 85% fuel utilisation

Case	Case I	Case II	Case III	Case IV	Case V	Case VI	Case VII
Gasifier temperature (°C)	900	900	900	950	950	950	900
Gasifier pressure (bar)	5	10	15	5	10	15	5
Fuel cell fuel utilisation (%)	70	70	70	70	70	70	70
Gasifier outlet flow (kg/s)	28.08	26.9	26.17	29.7	28.6	27.7	28.08
Mole fractions (%)							
CH ₄	4.5	5.4	6.1	3.4	4.1	4.7	4.5
H ₂	14.8	14.6	14.4	14.4	14.4	14.3	14.8
CO	19.1	19.5	19.8	18.9	19.4	19.8	19.1
CO ₂	10.6	10.8	10.9	9.9	10.0	10.1	10.6
H ₂ O	10.6	10.4	10.3	11.3	11.1	10.9	10.6
N ₂	39.6	38.3	37.5	41.1	40.0	39.2	39.6
H ₂ S	0.01	0.01	0.01	0.009	0.01	0.01	0.01
NH ₃	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Tar	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Thermal input (LHV (kW))	194728	194728	194728	194728	194728	194728	194728
Thermal input (HHV (kW))	208927	208927	208927	208927	208927	208927	208927
Fuel cell fuel utilisation 70%							
Power output MCFC (kW)	38259	36892	36068	39813	38846	38118	58472
Steam turbine (kW)	23808	24059	23934	23772	23515	23362	18614
Anode expander (kW)	0	3205	5315	0	3372	5580	0
Cathode expander (kW)	15951	15139	15724	15089	15816	15923	13686
Gross power (kW)	78018	79295	81041	78674	81549	82983	90772
FC air compressor (kW)	4621	3679	4079	4051	4563	4576	4365
Anode recycle (kW)	1453	1396	1363	1525	1473	1437	1655
Cathode recycle (kW)	5352	4892	4583	6477	5978	5706	5716
Gasifier compressors (kW)	3257	4808	5741	3593	5343	6364	3257
Other auxiliaries (kW)	5678	6084	6354	5182	5548	5765	3845
Net consumption	20361	20859	22120	20828	22905	23848	18828
District heat (kW)	102505	103416	103280	103157	103315	102685	90763
Net power (kW)	57657	58436	58921	57846	58644	59135	71934
Power efficiency (% LHV)	29.6	30.0	30.3	29.7	30.1	30.4	36.9
Overall efficiency (% LHV)	82.2	83.1	83.3	82.7	83.2	83.1	83.6
Fuel cell fuel utilisation 85%							
Power output MCFC (kW)	46457	44797	43797	48345	47171	46286	71002
Steam turbine (kW)	21330	19937	19823	19567	18985	19147	13756
Anode expander (kW)	0	3205	5315	0	3372	5580	0
Cathode expander (kW)	23095	25721	26009	27000	26658	26154	13572
Gross power (kW)	90882	93660	94944	94912	96186	97167	103133
FC air compressor (kW)	12231	14431	14534	16119	15619	15039	4935
Anode recycle (kW)	1484	1427	1394	1558	1505	1469	1675
Cathode recycle (kW)	7047	5410	5022	6319	6201	6205	5255
Gasifier compressors (kW)	3257	4807	5741	3593	5343	6363	3257
Other auxiliaries (kW)	4794	5214	5504	4249	4633	4867	3241
Net consumption	28813	31289	32195	31838	33301	33943	18363
District heat (kW)	95033	94480	94593	92294	93989	93834	83731
Net power (kW)	62069	62371	62749	63074	62885	63224	84770
Power efficiency (% LHV)	31.9	32.1	32.2	32.4	32.3	32.5	43.5
Overall efficiency (% LHV)	80.7	80.5	80.8	79.8	80.6	80.7	86.5

The calculations were then carried out at two discrete temperature levels, 900 and 950 °C, which adds up to six different operational modes (cases I–VI). In addition to these, one calculation was carried out at a gasifier pressure of 5 bar and 900 °C assuming internal reforming taking place within the MCFC stack (case VII). In order to investigate the effect of fuel utilisation in the fuel cell, the overall system performance for all operational points were calculated assuming a 70 and 85% fuel utilisation in the fuel cell. Summaries of the overall system characteristics found in the investigated cases are shown in Table 4. In addition to this, the effect of an average cell voltage increase was studied. When viewing the results in Table 4, one has to keep in mind that the results presented here are for a flowsheet that is not optimised with respect to heat utilisation.

6. Discussion

When comparing the gasifier gas compositions in Table 4, to the results obtained in a real gasifier [46], it was found that the compositions agree within a few percent. When observing the results in Table 4, it can easily be seen that on an overall system level, the only factor that significantly influences the net power generation is if internal reforming is included or not, whereas both temperature and pressure of the gasifier has an negligible influence. It is, however, important to recognise that the fuel cell model used does not account for differences in gas composition, and a more detailed stack model should be used to confirm the findings beyond reasonable doubt. When studying the individual results for the different power generation and consumption sections, variations can be observed.

6.1. Effect of gasification pressure: cases I–III and IV–VI

If comparing the results at an individual gasifier temperature level, it can be noted that the power produced by the fuel cell itself decreases with increasing gasifier pressure. There are two different factors combining to give this result. At first, an increasing pressure leads to decreased hydrogen content and an increased carbon monoxide content of the produced gas. As both species are assumed to be equally consumed by the fuel cell, these effects could very well level out, if it were not for a third aspect. The yield model based on the Vattenfall data that was used in this study has the feature that at higher gasifier pressures, less air is fed to the gasifier. As a consequence, the product gas flow from the gasifier will decrease, thus lowering the amount of reactants being fed to the anode. Someone might object that this is a result of an ill-designed gasifier, but since this study is dependent on the gasifier values supplied by a study carried out by Vattenfall, the design of the gasifier could not be a variable in this study.

Another feature of the gasifier model is that not only does the overall gas production decrease with increasing pressure, but so does the reactants available for electrochemical

conversion (i.e. H₂ and CO). This together with the fact that the fuel cell model used does not account for changes in pressure or gas composition leads to the lower power output of the fuel cell section.

The observed drop in fuel cell power generation leads to a decreased need for stack cooling by excess cathode gas flow. As a result a smaller cathode gas recycle flow is needed, thus resulting in a decreased power need for the cathode recycle blower. This lower need for cooling also has the consequence that more of the gas leaving the cathodes can be sent to the cathode expander, resulting in an increased power production in this specific unit.

For the steam turbines, a slight decrease in the power produced can be observed with an increasing pressure. This is because at higher pressures, the fraction of carbon monoxide to hydrogen increases. In order to ensure that the water-gas shift reaction (4) is maintained, steam is added to the purified gas prior to anode entry. This steam is withdrawn from an intermediate expansion step between the steam turbines, and thus an increased carbon monoxide content will result in a lower mass-flow through some of the steam turbine expansion steps. As a consequence, the power production of the steam turbine will decrease.

6.2. Effect of gasification temperature: cases I versus IV, II versus V and III versus VI

When comparing two operational points with the same gasifier pressure, but different temperature levels, e.g. cases I and IV, it was found that when raising the gasifier temperature, the power produced by the fuel cell will increase as a result of an increased product gas flow from the gasifier. This increase counteracts the slight decrease in hydrogen and carbon monoxide concentration in the gasifier product gas. The increased gas flow through the anode side also has another beneficial influence. In combination with a slightly increased cathode off-gas recycle, it results in a reduced need for fresh air, thus reducing the power needed for air compression.

6.3. Effect of fuel utilisation in the fuel cell

When comparing the results between 70 and 85% fuel utilisation by the fuel cell it can be noted that the 21% increase in fuel utilisation will lead to a 20% increase of power produced by the fuel cells. This increase is, however, countermeasured by a decrease of the power produced by the steam turbines when compared to the 70% fuel utilisation case. As a result, the overall increase in power production will be only about 6%.

6.4. Effect of average fuel cell voltage

In order to investigate how an improvement in cell voltage would influence the performance of the system; the average cell voltage was increased by 10% when operating

the gasifier at 900 °C and 10 bar. The results observed were that the power production of the fuel cells increased by 10%, whereas the power produced by the steam turbines decreased with about 7%. Together with a observed drop in the power generated by the cathode expander of about 7%, the overall power production with fuel cells and turbines included only increased by less than 1%. Because of a slight decrease in internal plant power consumption, the power efficiency increased by 3.4%. The overall efficiency remained virtually unaffected by the 10% increase in cell voltage.

6.5. The effect of internal reforming

The most significant effect on the efficiency, as already mentioned, is the introduction of internal reforming, case VII. In this case the net power production takes a considerable jump with about 23% with 70% fuel utilisation, and as much as 36% for the 85% fuel utilisation case. The reason for this is that CH₄ now is treated as a reactant, i.e. considerably more power corresponds to each of the fuel utilisation values. Some other aspects that can be observed is that both the power production by the cathode expander and the power consumption of the air compressor drops. This is a result of the lower need for air to cool the fuel cell stack, which instead is cooled by the internal reforming.

6.6. General observations

When looking at the power consumption of the gasifier compressors it is only natural to notice that an increased gasifier pressure demands a higher compression work for the gases entering the gasifier. Also the expander between the gasifier and anode is only adaptable in those cases where the gasification takes place at a pressure higher than the fuel cell operational pressure.

If the findings in this study are compared with other studies [32–38], it can be noticed that these cite electrical efficiencies ranging between 24 and 70%, compared to the 30–43% found in this study. A direct comparison of results can, however, be cumbersome as factors such as gasifier efficiency, high- or low-temperature gas cleaning, etc. has an influence on the overall efficiency. As mentioned before, the gasifier cold gas efficiency is about 80%, which means that after one of the first steps, 20% of the chemical energy in the biomass has been converted into heat, and is withheld from further electrochemical conversion. The other main causes for losses that result in an overall efficiency of about 80% are heat losses mainly associated with non-recoverable heat leaving the system together with the effluent streams. As an example only two-third of the heat used for biomass drying (33,800 kW) can be recovered by cooling the evaporated steam leaving the drier unit. Similarly heat is lost with the effluents leaving the system at 105 °C.

If comparing the obtained results with one of the few biomass IGCC powerplants built [11,13,14], having an electrical efficiency of about 30%, the biomass IGCC–

MCFC system well stands for an comparison. The above, in addition to a somewhat conservatively low cell voltage may, explain the somewhat low efficiencies obtained.

7. Conclusions

The present study suggests that biomass can be converted into electricity via a IGCC–MCFC process with an efficiency ranging from 30 to 43% depending on whether internal reforming is deployed or not. This is comparable with the biomass IGCC systems that have been operated on a demonstration level. The overall efficiency is in the range of 80–86%, when operated in a combined heat and power mode. In order to make a full evaluation of the system, a MCFC stack model accounting for gas composition, flow and pressure should be developed.

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