Feasibility study of wood biomass gasification/molten carbonate fuel cell power system—comparative characterization of fuel cell and gas turbine systems

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Abstract

The conversion of biomass by means of gasification into a fuel suitable for a high-temperature fuel cell has recently received more attention as a potential substitute for fossil fuels in electric power production. However, combining biomass gasification with a high-temperature fuel cell raises many questions with regard to efficiency, feasibility and process requirements. In this study, a biomass gasification/molten carbonate fuel cell (MCFC) system is modelled and compared with a relatively well-established biomass gasification/gas turbine (GT), in order to understand the peculiarities of biomass gasification/MCFC power systems and to develop a reference MCFC system as a future biomass gasification/MCFC power station.
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1. Introduction

Biomass is supposed to be an important energy source if a more sustainable production of electricity is required. Unfortunately biomass cannot be seen as a favourable fuel for producing electricity. The combination of biomass gasification with a high-temperature fuel cell (in this case, molten carbonate fuel cell (MCFC)) offers an opportunity of using biomass for producing electricity in decentralized power stations. However, the biomass gasification system combined with a fuel cell raises many questions with regard to technologies, which must be applied, and overall system efficiencies, which can be achieved. The selection of a suitable biomass gasification system for small to intermediate scale applications (approximately 1–10 MW$_e$) requires a careful evaluation of gasification processes and gas cleaning systems as well as options for system integration. In this study, a biomass gasification/MCFC system is modelled and compared with a preliminary biomass gasification/gas turbine (GT) system. The trends of MCFC output performance and the limited conditions of MCFC operation towards system parameters (operating pressure, CH$_4$ reforming rate and fuel moisture content) are discussed based on the comparison with the GT system. The comparative study is helpful in understanding the difference between the selection criteria of MCFC system and GT system and to develop a reference MCFC system used for investigating future technology and system designs for biomass gasification/MCFC power stations.

2. Model used within the study

The system models in this study are simplified models to help understand the difference between the selection criteria

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Nomenclature

A_i	frequency factor for resistance parameter in Eqs. (8)–(10)
E	open circuit voltage of MCFC (V)
F	Faraday constant (C/mol)
H	enthalpy (J/s)
J	current density (A/cm^2)
M	gas concentration (−)
m	specific mass flow rate (mol/s)
P	partial pressure (atm)
R	gas constant (J/mol/K)
R_a, R_c	anode, cathode reaction resistance of MCFC ($\Omega \, cm^2$)
R_{ir}	internal resistance of MCFC ($\Omega \, cm^2$)
S	stack area of MCFC (cm^2)
T	temperature (K)
U_f	fuel utilization of MCFC (−)
V	output voltage of MCFC (V)
W	output energy (W)

Greek letters

α	factor for describing CH$_4$ content of product gas (−)
ΔU	activation energy in Eqs. (8)–(10) (J/mol)
ε	efficiency (−)
η_{ne}	Nernst loss of MCFC (V)
ξ	reaction ratio of combustion to gasification in gasifier (−)

of an MCFC system and a GT system; the processes are not always described in detail. The flow sheet diagrams of the biomass gasification/GT system and the biomass gasification/MCFC system are shown in Figs. 1 and 2. The systems are composed of biomass gasifier, gas cleaning, GT and MCFC units. The gasifier and gas-cleaning units are common for GT and MCFC systems. The pressure loss of each piece of equipment is assumed to be 0.5–1% of the inlet pressure; the heat loss of the pipe has not been considered. For both systems, the plant scale is assumed to be 10 MW$_e$. The process simulation of the systems has been implemented with Visual Basic. The models of the units are described as follows.

2.1. Biomass gasifier and gas-cleaning units

Regarding the biomass gasifier model, several elements would have to be built to achieve a detailed mathematical model using mass and energy balances of the entire gasifier based on the reactions taking place, their specific reaction rates, the reaction heat of each reaction as well as the thermal constraints of the gasifier materials itself. This kind of model would be very complex and cumbersome to use. The development of a detailed model is not the aim of this study. Therefore, a simplified model for an air-blown, circulating
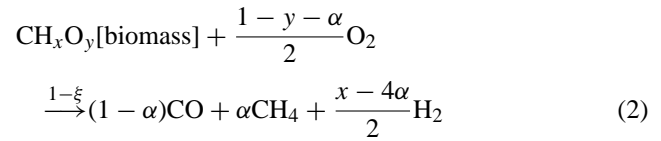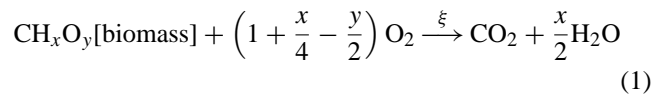
Table 1
Wood data

Elemental analysis		CH$_x$O$_y$
C (wt.%, daf)	50	1.00
H	6	1.43
O	44	0.66
Heating value		
HHV (MJ/kg, daf)	20.0	
LHV	18.7	
Moisture content (wt.%)		
	15* (5–50)	

daf: dry and ash free.
* Standard point.

fluidised-bed gasifier (CFBG) has been selected for this study. The reactions in the gasifier are thought to be a combustion reaction as shown in Eq. (1) and a gasification reaction as shown in Eq. (2).

$$CH_xO_y[\text{biomass}] + \left(1 + \frac{x}{4} - \frac{y}{2}\right)O_2 \xrightarrow{\xi} CO_2 + \frac{x}{2}H_2O \tag{1}$$

$$CH_xO_y[\text{biomass}] + \frac{1-y-\alpha}{2}O_2$$
$$\xrightarrow{1-\xi} (1-\alpha)CO + \alpha CH_4 + \frac{x-4\alpha}{2}H_2 \tag{2}$$

The values x, y are assumed to be 1.43 and 0.66, respectively, which are reported to be average values for wood [1]. Table 1 shows the data of wood used in the calculation. ξ in Eq. (1) indicates the reaction ratio of the biomass combustion, $1-\xi$ in Eq. (2) indicates that of the biomass gasification. The factor α in Eq. (2) is introduced to describe the CH$_4$ content of the product gas. When the temperature of the gasification is below 1000 °C, a report is drawn up saying that the product

Table 2
Input data and performance of gasifier unit

Input data	
Carbon conversion (%)	95
Heat loss (%, input fuel HHV)	5
CH$_4$ ratio factor (%)**	15
Outlet temperature (°C)	850
Outlet pressure (arm)	8* (2–20)
Performance on standard point	
Air equivalence ratio (%)	33.6
HHV of product gas (MJ/Nm^3, wet base)	5.14
HHV of product gas (MJ/Nm^3, dry base)	5.83
Cold gas efficiency (%, input fuel HHV)	72.2
Product gas H$_2$ (vol.%)	13.7
CO	16.0
CO$_2$	12.1
CH$_4$	3.5
N$_2$	43.1
H$_2$O	11.7

* Standard point.
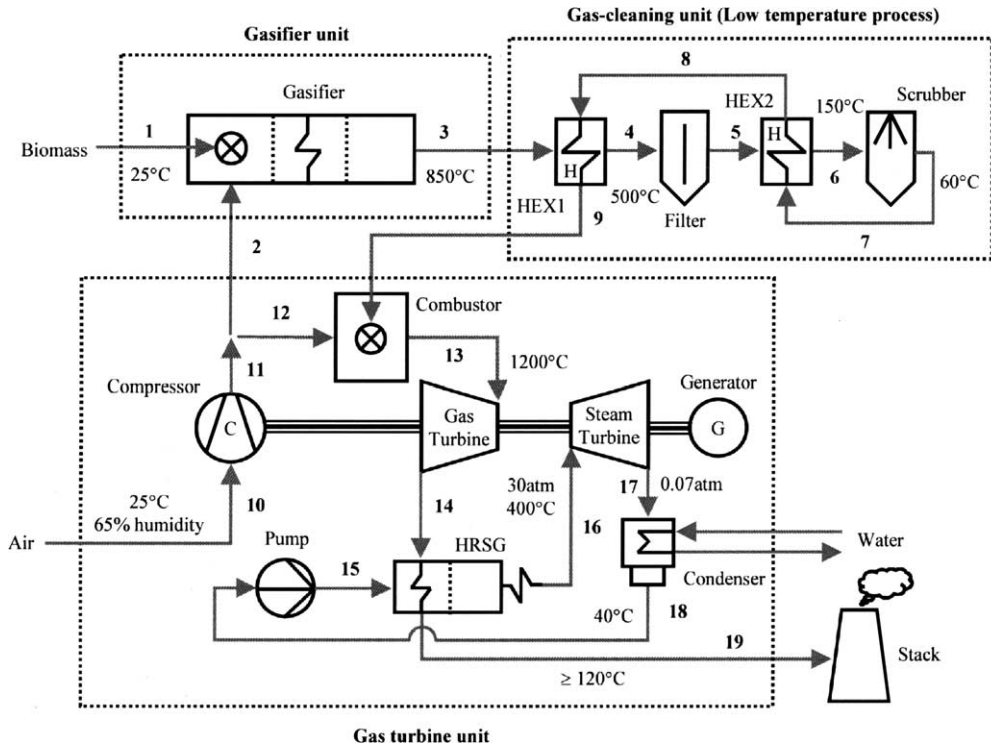** Correspondence to α in Eq. (2)

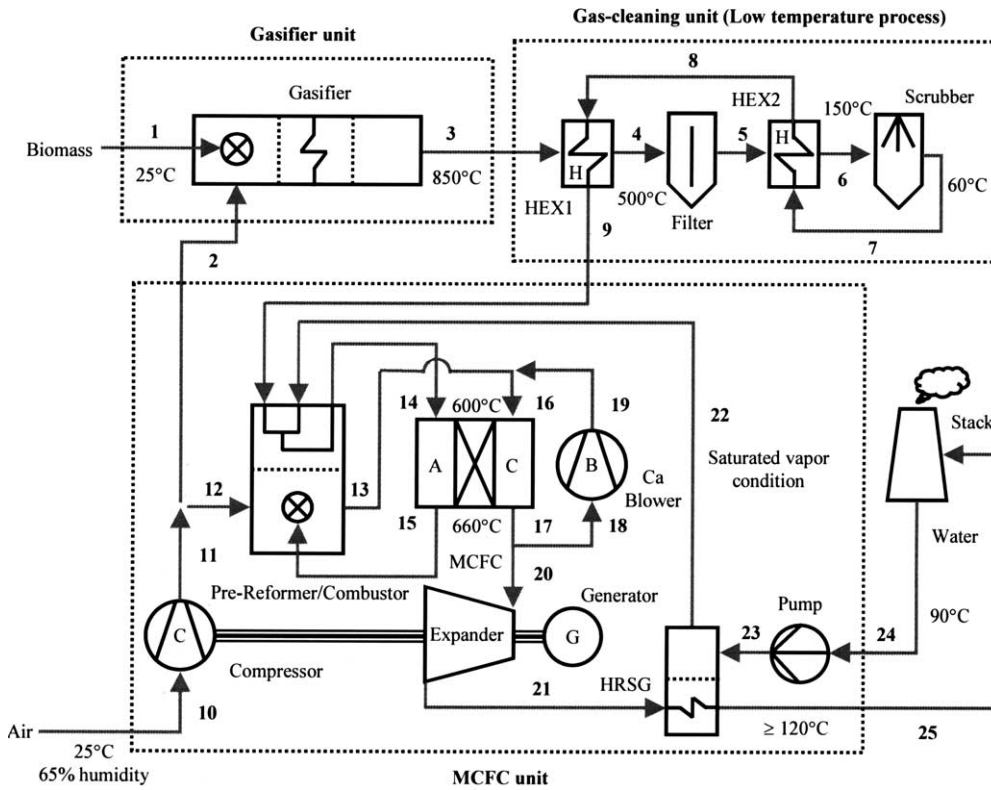Fig. 1. Flow sheet diagram of biomass gasification/GT system.

Fig. 2. Flow sheet diagram of biomass gasification/MCFC system.

gas contains several percent CH_4 [2,3]. The value α is set at 15% to represent about 4% CH_4 of the product gas. Table 2 shows the input data and the performance of the gasifier unit. The input data of the gasifier is a carbon conversion of 95%, 5% heat loss of the input fuel HHV and an outlet temperature of 850 °C. The composition of the product gas is determined by the values of the input data. The value of the air equivalence ratio, which provides the value ξ, is necessary to satisfy that of the heat loss in the gasifier. The composition of the product gas is also assumed to satisfy the equilibrium of the water gas-shift reaction shown in Eq. (3) at the temperature of the gasifier exit.

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \qquad (3)$$

The gasifier performance listed in Table 2 seems to simulate the typical gas characteristics of biomass gasification by air-blown CFBG well [2–6]. The calculation of the gasifier performance is based on a biomass moisture content of 15%. Typical moisture contents of freshly cut wood range from 30–60%, whereas most gasification systems use dry fed biomass with moisture contents of 10–20% in order to generate a product gas with a reasonably high heating value [6,7]. Some literature has discussed the effect the biomass moisture content has on the gasifier performance [2,6,8]. Fig. 3 shows the effect the moisture content has on the gasifier performance, which is obtained from the gasifier unit modelled here. The increase of the moisture content by approximately 5–50% leads to a large decrease of cold gas efficiency due to the increase of the equivalence ratio in an attempt to keep the exit temperature of the gasifier at 850 °C.

Regarding the gas cleaning model, a low-temperature process is chosen since this process is well established, whereas high-temperature processes are still undergoing development. Table 3 shows the input data of the gas-cleaning unit. The product gas leaving the gasifier is introduced into a filter and scrubber in order to remove impurities (particles,

Table 3
Input data of gas-cleaning unit

Heat exchanger (HEX)	
Heat loss (%, exchange heat)	10
Pinch point (°C)	30
HEX1 outlet temperature (°C)	500
HEX2 outlet temperature (°C)	150
Filter	
Heat loss (%, input heat)	5
Scrubber	
Temperature (°C)	60

tars, ammonia and NO_x, halogens, alkali compounds etc.) and meet the required levels [9–11] and finally cooled down to 60 °C. The cleaned gas leaving the scrubber is re-heated by heat exchangers before meeting the GT or MCFC unit. As long as a low-temperature process is chosen for the gas-cleaning unit, most of the steam in the product gas is condensed in the scrubber. The steam level decreases to the pressure level of saturated vapour, which corresponds to the temperature of the scrubber despite the fuel moisture content. Fig. 4 shows the effect of the fuel moisture content on the cleaned gas composition and the steam loss in the scrubber with a pressure of approximately 8 atm. The moisture content of the cleaned gas leaving the scrubber (60 °C) is about 3% at approximately 8 atm. At moisture contents of 5–50%, the steam loss, which is condensed in the scrubber, reaches 70–95% of the amount of steam contained in the product gas. The low-temperature process also results in a loss of sensible heat in the product gas despite recovering part of the heat from the product gas by using heat exchangers.

2.2. Gas turbine unit

The GT unit modelled in Fig. 1 consists of a GT, steam turbine (ST) and heat recovery steam generator (HRSG). Table 4 shows the input data of the GT unit. The inlet temperature and
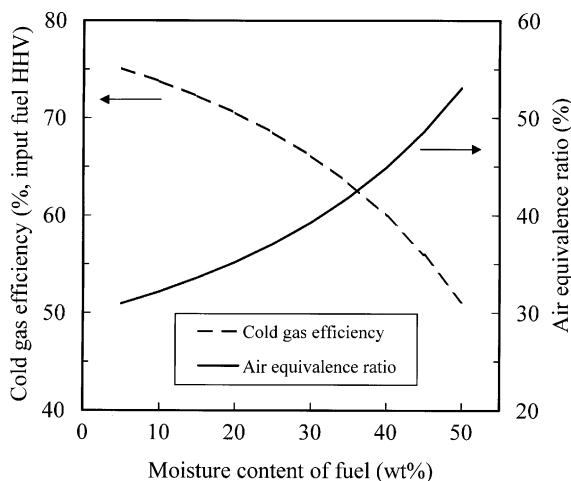

Fig. 3. Effect of moisture content on gasifier performance, carbon conversion = 95%; gasifier heat loss = 5%; gasifier outlet pressure = 8 atm; gasifier outlet temperature = 850 °C.
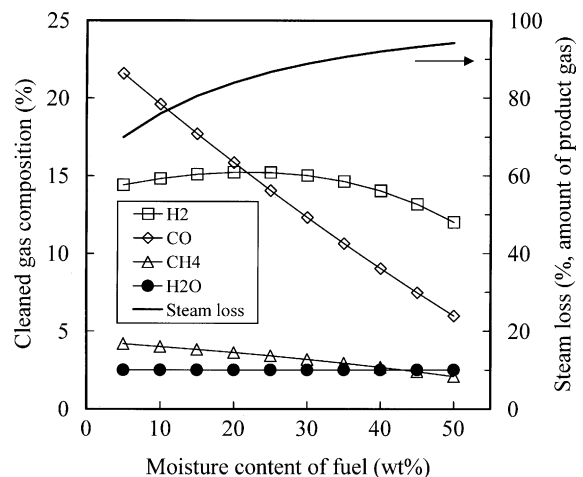

Fig. 4. Effect of moisture content on cleaned gas composition and steam loss during low-temperature process; scrubber pressure = 7.84 atm; scrubber temperature = 60 °C.

Table 4
Input data of GT unit

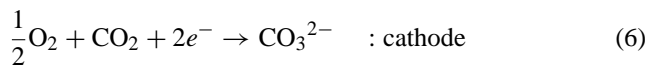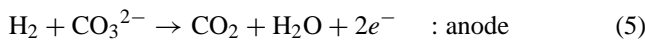| Gas turbine (GT)	
Isentropic efficiency (%)	85
Inlet temperature (°C)	1200
Outlet pressure (atm)	1.05
Combustor heat loss (%)	0
Compressor (Compr.)	
Isentropic efficiency (%)	85
Steam turbine (ST)	
Isentropic efficiency (%)	70
Steam temperature (°C)	400
Steam pressure (atm)	30
Heat recovery steam generator (HRSG)	
Heat loss (%, steam production heat)	10
Pinch point (°C)	10
Min. temperature of outlet flue gas (°C)	120
Condenser	
Temperature (°C)	40
Generator	
Efficiency (%)	98

isentropic efficiency of the GT are set at 1200 °C and 85%. The expanded gas leaving the GT is passed to the HRSG in order to be used for steam production and is exhausted in the stack. The steam conditions at the ST inlet are set at 400 °C and 30 atm; the isentropic efficiency is set at 70% based on a diagram comparing cycle efficiency with the thermal input in superheated steam [12]. The temperature of the exhausted gas leaving the HRSG has to satisfy the HRSG pinch point margin of 10 °C, but should not be lower than 120 °C.

2.3. Molten carbonate fuel cell unit

The MCFC unit modelled in Fig. 2 consists of a pre-reformer, MCFC, expander and HRSG. Table 5 shows the input data of the MCFC unit. The re-heated cleaned gas leaving the gas-cleaning unit is introduced into the pre-reformer located in front of the MCFC in order to convert the CH_4 in the fuel gas. The reforming reaction is as follows:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{4}$$

The inlet and outlet temperatures of the MCFC are set at 600 °C and 660 °C, respectively. The current density and fuel utilization are set at 200 mA/cm^2 and 80%. The electrochemical reactions of the MCFC are as follows:

$$H_2 + CO_3{}^{2-} \rightarrow CO_2 + H_2O + 2e^- \quad : \text{anode} \tag{5}$$

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3{}^{2-} \quad : \text{cathode} \tag{6}$$

The field in which reactions (4) and (5) occur is always assumed to satisfy the equilibrium of the water gas-shift reaction shown in Eq. (3). Regarding the MCFC performance, which corresponds to the output voltage (V) under load, the following model [13] is used to evaluate the performance.

$$V = E - \eta_{ne} - (R_{ir} + R_a + R_c) \times J \tag{7}$$

Table 5
Input data of MCFC unit

Molten carbonate fuel cell (MCFC)	
$A_{ir}(\Omega\,cm^{-2})$	1.40×10^{-2}
ΔU_{ir} (kJ/mol)	23.0
$A_a(\Omega\,cm^2\,atm^{0.5})$	2.04×10^{-3}
ΔU_a, (kJ/mol)	23.7
$A_{c1}(\Omega\,cm^2\,atm^{0.25})$	3.28×10^{-9}
ΔU_{c1} (kJ/mol)	132
$A_{c2}(\Omega\,cm^2)$	3.39×10^{-6}
ΔU_{c2} (kJ/mol)	67.1
$A_d(\Omega\,cm^2)$	2.00×10^{-1}
Heat loss (%)	0
Current density (mA/cm^2)	200
Fuel utilization (%)	80
Inlet temperature (°C)	600
Outlet temperature (°C)	660
Pre-reformer/combustor	
CH$_4$ reforming rate (%)	95* (0–95)
Combustor heat loss (%)	0
Expander (Expan.)	
Isentropic efficiency (%)	85
Outlet pressure (atm)	1.05
Blower	
Isentropic efficiency (%)	70
Mechanical efficiency (%)	95
Inverter	
Efficiency (%)	97

* Standard point.

$$R_{ir} = A_{ir}\exp\left(\frac{\Delta U_{ir}}{RT}\right) \tag{8}$$

$$R_a = A_a\exp\left(\frac{\Delta U_a}{RT}\right) P(H_2)^{-0.5} \tag{9}$$

$$R_c = A_{c1}\exp\left(\frac{\Delta U_{c1}}{RT}\right) P(O_2)^{-0.75} P(CO_2)^{0.5}$$
$$+ \frac{A_{c2}\exp(\Delta U_{c2}/RT)}{A_d M(H_2O) + M(CO_2)} \tag{10}$$

E, η_{ne}, R_{ir}, R_a, R_c and J are the open circuit voltage, Nernst loss, internal resistance, anode reaction resistance, cathode reaction resistance and current density, respectively. The temperature determining the output voltage is set at 630 °C, which is the average temperature between the inlet and outlet of the MCFC. The heat balance of the MCFC is assumed as follows:

$$H_{cathode\,out}(No.17) = H_{anode\,in}(14) + H_{cathode\,in}(16)$$
$$- H_{anode\,out}(15) - W_{FC} \tag{11}$$

H is a total enthalpy at each stream of Fig. 2 and W_{FC} is the MCFC output. W_{FC} is defined by Eq. (12).

$$W_{FC} = V \times J \times S = VJ \times \frac{2FU_f(m_{H_2}(14) + m_{CO}(14))}{J}$$
$$= 2FU_f V(m_{H_2}(14) + m_{CO}(14)) \tag{12}$$

S, F, U_f and m are the stack area, Faraday constant, fuel utilization and specific mass flow rate, respectively. According to Eq. (12), the MCFC output in this model is determined by the values of the output voltage (V) and the mass flow rate of H_2 and CO at the anode inlet ($m_{H_2} + m_{co}$) because the fuel utilization (U_f) is constant at 80%. Due to the amount recycled by the cathode blower (No. 19), the inlet temperature at the cathode is set at 600 °C, whereas due to the amount of air introduced into cathode through the combustor of the pre-reformer (No. 13), the outlet temperature at the cathode is set at 660 °C. The cathode gas leaving the MCFC is led to the expander in order to generate power. The expanded gas is cooled in the HRSG to generate steam and finally exhausted through the stack. The specifications of the HRSG are the same as that of the HRSG in the GT system of Fig. 1. The steam produced in the HRSG is introduced into the pre-reformer in order to be used for CH_4 reforming and to prevent carbon deposition at the anode inlet of the MCFC. The condition of the steam introduced into the pre-reformer is a saturated vapour condition corresponding to the pressure of the pre-reformer inlet (No. 9).

3. Results and discussion

Although several factors have an effect on the performances of the systems described in Figs. 1 and 2, the effects of the system pressure, CH_4 reforming rate and fuel moisture content are discussed to be able to understand the differences between the selection criteria of the GT system and the MCFC system. The outputs of Figs. 1 and 2 including compressor, expander, generator and inverter are defined as follows:

$$W_{GT/Compr.} = \varepsilon_{generator} \times (W_{GT\,output} - W_{compressor\,work})$$

$$(13)$$

$$W_{ST} = \varepsilon_{generator} \times W_{ST\,output} \qquad (14)$$

$$W_{MCFC} = \varepsilon_{inverator} \times W_{FC} \qquad (15)$$

$$W_{Expan./Compr.} = \varepsilon_{generator} \times (W_{expander\,output}$$
$$- W_{compressor\,work}) \qquad (16)$$

The performance of the GT system consists of $W_{GT/Compr.}$ and W_{ST}, whereas that of the MCFC system consists of W_{MCFC} and $W_{Expan./Compr.}$.

3.1. Effect of system pressure

The pressure at the gasifier exit varies from 2 atm to 20 atm. An increase of the gasifier pressure causes for an increase of the pressure in the GT and MCFC units. The pressure ratio of GT and compressor increases in the GT unit, whereas the pressure ratio of the expander and the compressor, and the pressure of the pre-reformer, MCFC and steam, which is passed to the pre-reformer, increases in the
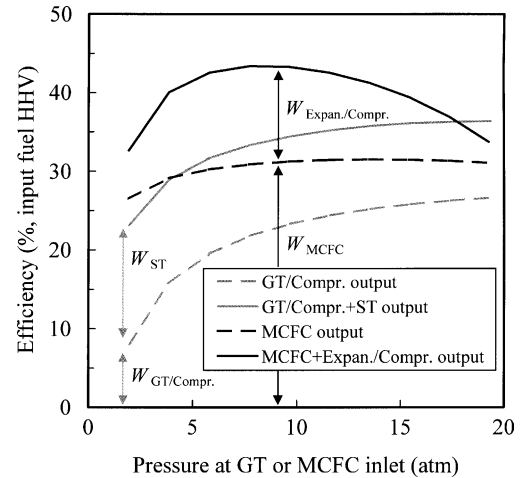

Fig. 5. Effect of pressure on GT and MCFC system performances, fuel moisture content = 15%.

MCFC unit. Fig. 5 shows the effect of pressure on the performance of the GT and MCFC systems. The performance of the GT system gradually increases by increasing the pressure, whereas the MCFC output (W_{MCFC}) beyond 6 atm is relatively independent of the pressure, and consequently, the performance of the MCFC system has an optimum point around 8 atm. The reason for this optimum pressure point is due to the balance between the expander output and the compressor working towards increasing pressure. According to Eq. (12), the MCFC output is proportional to the output voltage (V). Fig. 6 analyses the effect pressure has on the MCFC performance between 2 atm and 10 atm based on the model described in Eqs. (7)–(10). The pressure gain of the output voltage in Fig. 6 is relatively small beyond 6 atm.
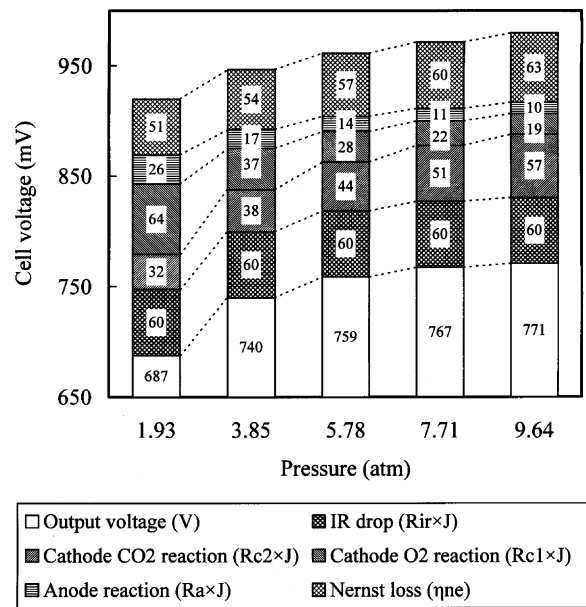

Fig. 6. Analysis of effect pressure on MCFC performance, temperature = 630 °C; current density = 200 mA/cm²; fuel utilization = 80%.

The reason for the trend in the MCFC performance beyond 6 atm is mainly due to the increase of the cathode carbon dioxide reaction resistance corresponding to the second term in Eq. (10). The system pressure increase causes for a composition deviation of the cathode stoichiometric ratio ($CO_2/O_2 = 2$ in Eq. (6)), because the increase of the pressure ratio at the compressor boosts the air temperature for cooling the MCFC and is responsible for increasing the amount of air introduced to the cathode of the MCFC.

Regarding the MCFC operation under pressurized conditions, it is required that the enough amount of steam is introduced into the MCFC to prevent carbon deposition at the anode inlet. In general, the criterion for preventing carbon deposition in the MCFC is based on the equilibrium line between the water-gas shift reaction (3) and the Boudouard reaction (17) [14].

$$2CO \Leftrightarrow C + CO_2 \tag{17}$$

Fig. 7 shows the carbon deposition criteria compared to the pressures in the C–H–O ternary diagram according to which the addition of steam is necessary for the cleaned gas to leave the low-temperature gas cleaning process and escape from the carbon deposition area. The amount of steam necessary increases by increasing the pressure. Fig. 8 shows the effect pressure has on the amount of steam, which is passed to the MCFC. The minimum amount of steam necessary to prevent carbon deposition increases by increasing the pressure, whereas the steam generated by the HRSG decreases by increasing the pressure. According to this analysis of steam balance, an operation of MCFCs at more than 9 atm possibly runs the risk of carbon deposition. The reasons for decreasing the quantity of steam generated by the HRSG are mainly two factors. One is the decrease of flue gas enthalpy to the HRSG resulting from the greater expander output due to the increased pressure ratio. The other is the increase of the gas temperature exhausted from the HRSG due to the in-
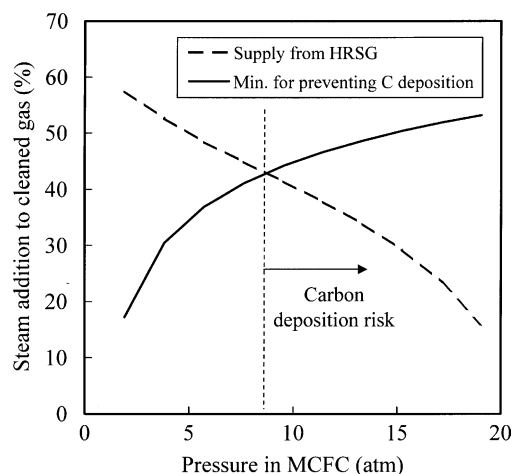

Fig. 8. Effect of pressure on amount of steam passed to MCFC, fuel moisture content = 15%; MCFC inlet temperature = 600 °C; HRSG pinch point = 10 °C.

crease of saturated vapour pressure in the steam. After all, the exhaust gas temperature must satisfy the HRSG pinch point margin. Another method to prevent the carbon deposition is the introduction of an anode recycling system in the form of an anode blower. However, an anode recycling system is thought to be unfit for a small-scale plant such as a biomass gasification system. If an anode recycling system was introduced, the plant scale would have to be much larger, similar to an integrated coal gasification MCFC (IG/MCFC) [15]. Therefore, the pressure range of the biomass gasification/MCFC system for decentralized power stations should be less than about 8 atm with regard to efficiency and operating constraints. When applying a high-temperature gas cleaning process, the operational pressure range of the MCFC expands, because the steam wasted in the scrubber during low-temperature processes is used effectively in the MCFC.

3.2. Effect of CH₄ content in product gas

In the MCFC unit modelled here, a pre-reformer is fitted in front of the MCFC in order to reform the CH_4, which is an ingredient of the cleaned gas, whereas the fuel, which is converted during the electrochemical reaction in high-temperature fuel cells consists of both, H_2 and CO, and not CH_4. Fig. 9 shows the effect the CH_4 reforming rate has on the MCFC system performance. When increasing the reforming rate from 0 to 95%, the CH_4 content of the cleaned gas changes slightly from about 4% to almost 0. However, the effect the reforming rate has on the MCFC output is significant. As the output of the MCFC decreases at lower reforming rates, the output of the MCFC around 8 atm is lower than that of the GT/compressor in the GT system on the condition of 20% lower reforming rates. Therefore, reforming several percent of the CH_4 in the biomass product gas according to Eq. (4) is a key factor to improve the MCFC
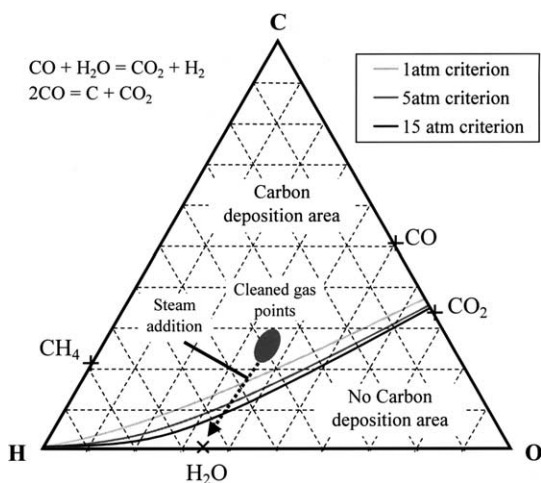

Fig. 7. Ternary diagram showing carbon deposition criteria compared to pressures at temperature of 600 °C, fuel moisture content = 15%.
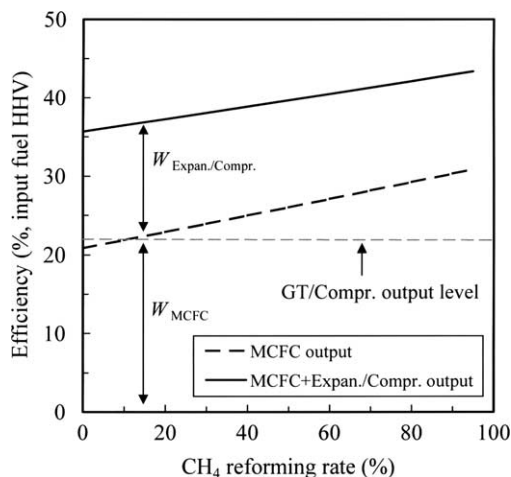
Fig. 9. Effect of CH_4 reforming rate on MCFC system performance, fuel moisture content = 15%; MCFC pressure = 7.71 atm; GT pressure = 7.75 atm.

output because the output of the MCFC defined by Eq. (12) is proportional to the amount of H_2 and CO.

3.3. Effect of fuel moisture content

Fuel with a moisture content above about 30% makes ignition difficult and reduces the calorific value of the product gas due to the desire to evaporate the additional moisture before combustion/gasification can occur [16]. Therefore, the biomass moisture content should be below $10-20\%$ before gasification. The moisture content in biomass differs between raw biomass, which refers to the biomass at the plant gate, and the fed biomass, which refers to the biomass entering the gasifier after drying [6]. However, literature discussing the biomass gasification/MCFC system suggests that fed biomass does not need to be dried [17]. Fig. 10 shows the effect of the moisture content on the GT and MCFC system performances. Although the moisture content of the cleaned
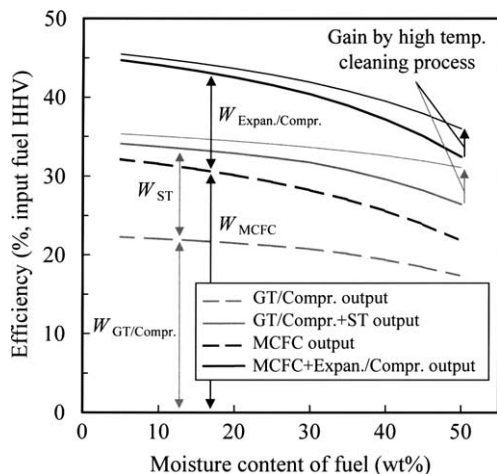

Fig. 10. Effect of moisture content on GT and MCFC system performances; GT pressure = 7.75 atm; MCFC pressure = 7.71 atm.

gas decreases to 3% at around 8 atm when leaving the scrubber as shown in Fig. 4, a higher fed moisture content decreases the GT and MCFC system performances by decreasing the gasifier performance as shown in Fig. 3. When comparing the variation of both system efficiencies regarding higher moisture contents, the power reduction due to the increased moisture content is larger in the case of the MCFC system than in the case of the GT system. The larger reduction in the MCFC system is due to the decrease of the MCFC output (W_{MCFC}). The factors determining the MCFC output are output voltage (V) and mass flow rate of H_2 and CO at the anode inlet ($m_{H_2} + m_{co}$) according to Eq. (12). The output voltage reflects the performance of the MCFC itself, whereas the mass flow rate reflects that of the gasifier. The reduction of the MCFC output is proportional to that of the cold gas efficiency, as shown in Fig. 3, because the value of the output voltage remains a constant (about 767 mV in this case) in the variation of the cleaned gas composition as shown in Fig. 4. A constant output voltage is determined due to the behaviour of the anode voltage drop under load. In general, the voltage loss due to the anode reaction resistance in the MCFC ($= R_a \times J$ in Eq. (7)) under pressurized conditions is smaller than the loss by other factors as shown in Fig. 6. The output voltage under pressurized conditions is relatively independent of the variation of the anode gas composition.

In the above discussion, a low-temperature process has been selected for the gas-cleaning unit. However, the low-temperature process provides the operating constraints described in Fig. 8 due to the steam wasted in the scrubber. Therefore, a high-temperature process, which has the function of removing the unwanted components from the product gas without wasting steam, is a key issue for a successful application of the biomass gasification/MCFC system. Regarding high-temperature process technologies for gas cleaning, the technologies are still undergoing development and involve many uncertain factors. In this study, a diagram modification shown in Fig. 11 is introduced to express the high-temperature process descriptively rather than quantitatively. The diagram should only be considered as a guideline for high-temperature processes performing gas cleaning. When applying a simple high-temperature process for gas cleaning instead of a low-temperature process, the steam wasted in the scrubber during low-temperature processes is able to pass into the MCFC without the loss shown in Fig. 4. The result of not wasting steam is the expansion of the operational pressure range in MCFCs as shown in Fig. 12. Independent of the gas cleaning temperature, the optimum point of pressure in high-temperature processes is the same as in low-temperature processes as described in Fig. 5. Regarding the efficiency gains in the GT and MCFC system performances by applying high-temperature processes, the increase is about $1-2\%$ at a moisture content of 15% (typical fed biomass) and about $4-6\%$ at 50% (typical raw biomass) in both systems. These gains increase by increasing the moisture content. This contributes towards resolving the disadvantage of the system efficiency, which is due to the use of a fuel

Gas-cleaning unit (Low temperature process)

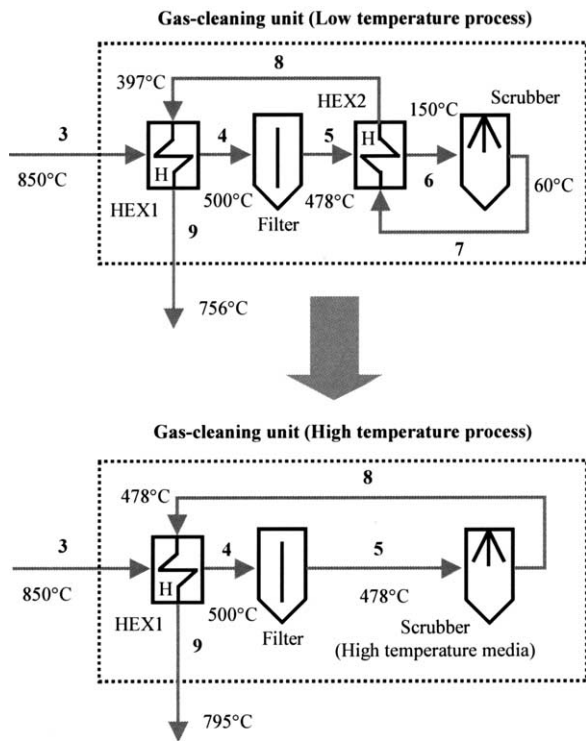## Gas-cleaning unit (High temperature process)

Fig. 11. Gas-cleaning diagram showing to modify low-temperature process to high-temperature process on both GT and MCFC systems, temperature profile based on gasifier outlet temperature = 8 atm and fuel moisture content = 15%.

with a higher moisture content, because the decrease of the system efficiency with higher moisture contents lessens by applying the high-temperature process. The use of fuel with a higher moisture content also reduces the cost of the dryer located in front of the gasifier. Therefore, the application of the high-temperature process would have the advantage of widespread deployment of biomass for power production.
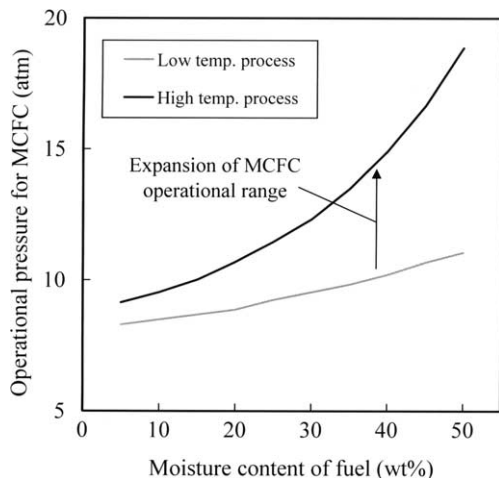

Fig. 12. Relation between moisture content and operational pressure range for MCFC on both processes in view of preventing carbon deposition; CH_4 reforming rate = 95%; MCFC inlet temperature = 600 °C; HRSG pinch point = 10 °C.

4. Conclusions

According to the results of the comparative characterization of GT and MCFC systems, a reference system, which is used for investigating future technology and system designs, in the form of a decentralized biomass gasification/MCFC or biomass gasification/GT power station is expected to have the following peculiarities.

MCFC unit; an operation of the MCFC over about 8 atm has no advantages with regard to the system efficiency or the operating constraint due to carbon deposition. The MCFC system prefers pressures ranging from 1 atm to 5 atm. In this range, the variation of the MCFC performance itself is relatively small compared to that of the GT performance and maintains a moderate efficiency (>25% input fuel HHV) even at nearly atmospheric conditions. Reforming almost all of the CH_4 included in the product gas has a significant influence on the MCFC performance. When the CH_4 content in the product gas is not converted to H_2 and CO before entering the MCFC, the MCFC output is possibly lower than the GT/compressor outputs over about 8 atm.

Gas-cleaning unit; high-temperature gas cleaning which is able to remove unwanted components from the product gas without wasting steam, is preferred in order to prevent carbon deposition in the MCFC and improve the decrease of GT and MCFC system efficiencies due to the use of a fuel with a higher moisture content.

Gasifier unit; the gasifier process is required to enable the gasification of biomass with higher moisture contents. The use of biomass with higher moisture contents is not always a disadvantage for the operation of the MCFC if high-temperature gas cleaning is applied. Moreover, in view of an ideal thermal integration between gasifier, gas cleaning and MCFC units, the temperature at the gasifier exit is preferred to be as close as possible to the temperature level of the MCFC (~600 °C). These requirements would decrease the gasifier performance such as carbon conversion or cold gas efficiency. However, the development of a gasifier process satisfying these requirements would provide an important advancement for decentralized biomass gasification/MCFC power stations.

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