

# Chapter 9

## Thermodynamic Analysis of a Cycle Integrating a Solid-Oxide Fuel Cell and Micro Gas Turbine with Biomass Gasification

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**Abstract** An integrated solid-oxide fuel cell-micro gas turbine system with biomass gasification is investigated based on energy and exergy. The system consists of a biomass gasification system, a solid-oxide fuel cell (SOFC), a micro gas turbine (MGT), and a heat recovery steam generator (HRSG). Various parameters are determined for the integrated system, including syngas molar fraction, and heat input to the gasifier. Moreover, exergy flows and exergy destruction rates of major components of the system are calculated. The maximum energy and exergy efficiencies of the gasification system are 65.7 and 84.8%, respectively. These values for the SOFC-MGT cycle with biomass gasification are reported as 58.3 and 69.6%. The variations of syngas molar fraction and mass flow rate, gasifier exergy destruction, and CO<sub>2</sub> emissions with the steam to carbon (SC) ratio are investigated. The results show that there is an optimum value for the SC ratio at which the syngas mass flow rates and the gasification energy efficiency reach a maximum. The CO<sub>2</sub> emission, which is an important factor for the sustainability of the system, increases by 19.4% as the value of the SC ratio increases. Increasing the gasification temperature, from 800 to 1000 °C, reduces the energy and exergy efficiencies of the total integrated system by 7.90%, mainly by increasing the required heat input to the gasifier.

**Keywords** Biomass gasification · Solid oxide fuel cell · Micro gas turbine · Energy · Exergy

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## 9.1 Introduction

Solid oxide fuel cells (SOFCs) are capable of producing electric power and heat in an integrated cycle. They can be integrated with micro gas turbines (MGTs) and heat recovery steam generators (HRSGs) to increase electricity and heat generation [1]. For instance, Motahar and Alemrajabi [2] report an exergy analysis of an integrated SOFC-GT cycle with and without steam injection to the combustion chamber of the gas turbine. They propose the use of the gas turbine flue gas in an HRSG and inject the produced steam in the combustion chamber. The exergy efficiency of the integrated system is seen to increase by 12% with steam injection. Moreover, they report the effects of compression ratio, current density, and the HRSG pinch point on system performance. Energy and exergy analyses of a hybrid fuel cell-gas turbine combined heat and power (CHP) system are reported by Akkaya et al. [3]. For exergetic performance evaluation, exergy efficiency, exergy output and exergy loss rate of the system are considered. Methane is used as the fuel and the molar fractions of the by-product species are reported for each point in the system [3]. In other systems, hydrogen, methane, and natural gas can be used as the fuel, but the integrated SOFC-MGT cycles are analyzed independent of the fuelling processes. Nevertheless, SOFCs can operate with different types of fuels, thanks to their internal reforming capability and high resistivity to carbon poisoning. However, higher hydrocarbons require pre-reforming or cracking before entering the fuel cell stack, because they decompose at conditions higher than the stack temperature [4].

With the increased attention on mitigation of carbon dioxide emission and other environmental considerations, the use of renewable energy resources in power generation is receiving much attention. Biomass can be used directly (direct burning) or indirectly (as a biofuel) to generate electricity [5]. Biomass gasification has been demonstrated to be a feasible and promising technology in the future energy market [6]. The gas mixture product of biomass gasification contains several species, depending on the process type and operational conditions. Stoichiometric calculations can help determine the products of reaction [7]. Abuadala and Dincer [8] consider the use of biomass gasification product gas as the fuel feed to a SOFC, as a potential, integrated application. In the present work, we consider a similar system in which the product gas is fed to the fuel cell stack after gas cleaning and CO<sub>2</sub> removal. The aim is to improve understanding of its performance, and this is accomplished by performing a parametric study of the effect of steam to carbon (SC) ratio on the performance of the SOFC-MGT cycle integrating biomass gasification. The variations in molar fraction and lower heating value (LHV) of the syngas (a mixture of H<sub>2</sub> and CO), and the gasification process exergy destruction and energy and exergy efficiencies are reported, as the steam to carbon ratio changes.

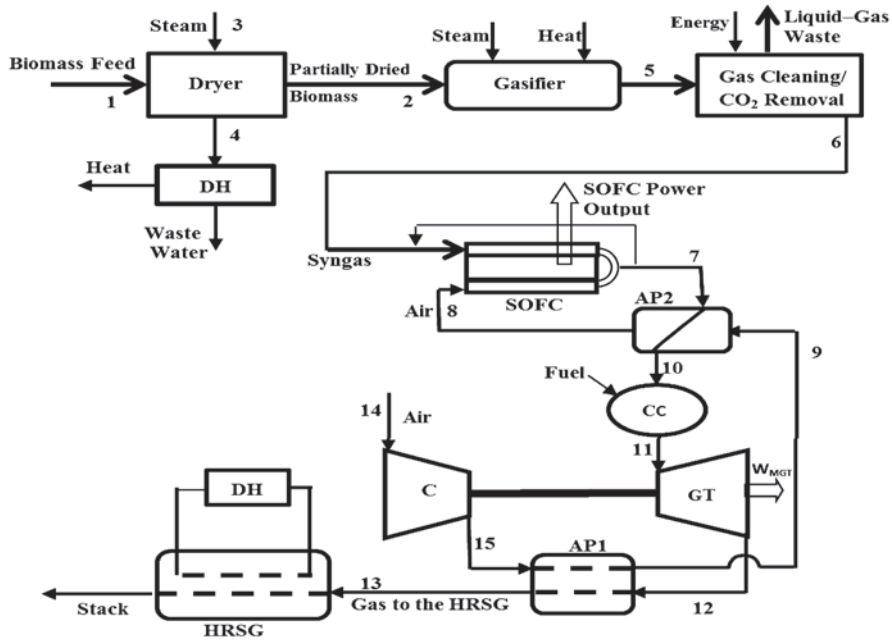


Fig. 9.1 Schematic of the integrated SOFC-MGT with biomass gasification

## 9.2 System Description

The integrated system includes a biomass gasification unit, an SOFC, a micro gas turbine and a heat recovery unit. Each of these systems consists of components, illustrated in Fig. 9.1, in which processes occur. Sawdust is fed to the biomass dryer before entering the gasifier. In the analyses, a direct-steam drying process is considered to remove 50% of the biomass moisture content. In the gasifier, biomass is converted to a mixture of gases in the presence of superheated steam. Biomass gasification is an endothermic process, and the gasification system is considered to be indirectly heated by an external heat source.

The product gas mixture leaving the gasifier contains CO, H<sub>2</sub>, CH<sub>4</sub>, CO<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub>, and C. The lower heating value (LHV) of the product gas is strongly dependant on the mixture composition. Moreover, downstream components in the integrated system are affected by the gas properties. Therefore, gas cleaning and CO<sub>2</sub> removal are added to the system. With these post-gasification processes, the product syngas consists of CO, H<sub>2</sub>, and CH<sub>4</sub> and is fed to the solid oxide fuel cell for power production.

The basic electrochemical reactions taking place in a SOFC stack are given by [1, 9]



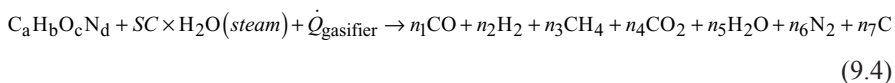


Characteristic curves of SOFCs are obtained based on the equilibrium constants and reaction rates of Eq. 9.1–9.3. The oxygen ions are formed in the cathode side of the fuel cell and pass through the electrolyte to the anode. The electrochemical reaction between hydrogen and oxygen ions releases electrons, which pass through an external electric circuit providing the power output of the SOFC. To avoid cell starvation, only a certain percent of the syngas reacts with oxygen ions in the anode. This is specified by fuel utilization factor. The by-product of the electrochemical reactions leaves the fuel cell stack with a temperature between 800 to 1000 °C. Also, the by-product contains some non-reacted syngas. In order to recover the energy from the SOFC exhaust gas, an afterburner is utilized to burn the remaining syngas and provide the micro gas turbine with the required input energy. Therefore, the by-product gas leaving the fuel cell anode side mixes with the air from the cathode side. The combustion process in the afterburner produces a high-enthalpy gas which can be used in the MGT for electric power generation. Before the combustion gas enters the micro gas turbine, it is utilized to preheat the air entering the fuel cell stack. The combustion chamber of the micro gas turbine is used to fix the turbine inlet temperature (TIT). The combustion gases enter the MGT, produce mechanical energy, and leave the MGT with a temperature between 550 and 750 °C, depending on the compressor pressure ratio. The mechanical energy of the MGT is converted into electricity in the generator. The MGT flue gas has a significant amount of energy, which is recovered in the heat recovery steam generator. The flue gas enters the HRSG and transfers its energy to the water flowing inside the tubes of the HRSG. Unless applied for power generation purposes, most HRSGs produce saturated steam for steam utilizing units.

### 9.3 Analyses

#### *Biomass Gasification System*

Superheated steam is used as the gasification medium in the gasifier. Sawdust is gasified in the presence of steam according to the following overall chemical equation:



Minimization of the Gibbs Free Energy is used [7, 10] to obtain the reaction coefficients ( $n_1$  to  $n_7$ ). To calculate the gasifier heat input, the steady-state energy balance is used:

$$\dot{n}_{mb,2} \left( h_{mb,2}^f + \bar{h}_{mb,2} - h_{mb,2}^0 \right) + \dot{n}_s \left( h_s^f + \bar{h}_s - h_s^0 \right) + \dot{Q}_{gasifier} = \left[ \sum_{i=1}^7 \dot{n}_i \left( h_i^f + \bar{h}_i - h_i^0 \right) \right]_p \tag{9.5}$$

Here,  $h_{mb,2}^f$  is the enthalpy of formation of biomass, which is affected by the moisture content of the biomass,  $\bar{h} - h^0$  is the sensible heat of the material relative to the reference state, which is the ambient condition. Further, “mb” refers to moist biomass and “s” to steam. Also,  $\dot{n}_i$  denotes the molar flow rate of the species in the reaction, and the subscript “i” refers to the product species. The enthalpy of formation and the sensible heat of the product gas, a gas mixture, are calculated based on the data and approach presented by Borgnakke and Sonntag [11].

A steady-state exergy balance for the gasifier follows:

$$\dot{E}x_{mb,2} + \dot{E}x_s + \dot{E}x_Q = \dot{E}x_p + \dot{I}_{gasifier} \tag{9.6}$$

The biomass dryer and district heating unit are parts of the gasification system. The necessary energy and exergy balance equations, which lead to the calculation of steam input to the dryer and heat flow rate of the district heating unit, are presented in a previous paper [10]. Considering these two components, the total energy and exergy efficiencies respectively of the gasification system can be obtained:

$$\eta_{gasification} = \frac{\dot{m}_{syngas} \times LHV_{syngas} + \dot{Q}_{DH}}{\dot{m}_{biomass} \times LHV_{biomass} + \dot{E}n_{Steam} + \dot{Q}_{gasifier} + \dot{E}n_{gas-cleaning}} \tag{9.7}$$

$$\psi_{gasification} = \frac{\dot{m}_{syngas} \times ex_{syngas} + \dot{E}x_{q,DH}}{\dot{m}_{biomass} \times ex_{biomass} + \dot{E}x_{Steam} + \dot{E}x_Q + \dot{E}x_{gas-cleaning}} \tag{9.8}$$

In Eqs. 9.7–9.8, steam use is considered for both the dryer and the gasifier.

### SOFC-MGT System

Colpan et al. [12] present a model for the electrochemical reaction in the SOFC. Their model considers a mixture of  $H_2$ , CO and  $CH_4$  as the syngas fuel. In the present paper, the same gas species are used in the fuel cell. The electric power output of the fuel cells stack can be expressed as

$$\dot{W}_{SOFC} = V \times i \times A_{cell} \times N_{SOFC} \tag{9.9}$$

where  $V$  is the output voltage,  $i$  is the current density,  $A_{\text{cell}}$  is the single cell active area, and  $N_{\text{SOFC}}$  is the total number of cells in the stack.

The modeling of the afterburner and the combustion chamber is based on combustion reactions of the remaining syngas in the fuel cell exhaust gas and the gas turbine inlet temperature. The gas turbine and the compressor are modeled based on isentropic relations and isentropic efficiencies. Therefore, the compressor outlet air temperature is obtained as follows [13]:

$$T_{\text{oc}} = T_{\text{ic}} \left\{ 1 + \frac{1}{\eta_c} \left( [rc]^{\frac{\gamma_a-1}{\gamma_a}} - 1 \right) \right\} \quad (9.10)$$

where  $T_{\text{oc}}$  and  $T_{\text{ic}}$  are the compressor outlet and inlet air temperatures,  $\eta_c$  is the compressor isentropic efficiency,  $rc$  is the compression ratio, and  $\gamma_a$  is the specific heat ratio of air.

A similar relation is used to calculate the exhaust gas temperature of the gas turbine:

$$T_{\text{omGT}} = T_{\text{IT}} \left\{ 1 - \eta_{\text{MGT}} \left( 1 - [rc]^{\frac{\gamma_g-1}{\gamma_g}} \right) \right\} \quad (9.11)$$

Here,  $T_{\text{oc}}$  and  $T_{\text{ic}}$  are the gas turbine outlet and inlet gas temperatures,  $\eta_{\text{MGT}}$  is the MGT isentropic efficiency,  $rc$  is the compression ratio, and  $\gamma_g$  is the specific heat ratio of gas. The temperatures are calculated to obtain the specific work quantities of the compressor and the gas turbine.

The gases leaving the MGT are fed to the HRSG to produce steam for steam/hot water utilization purposes. Accounting for the heat recovered in the HRSG, the total efficiencies of the SOFC-MGT CHP system are

$$\eta_{\text{SOFC-MGT CHP}} = \frac{\dot{W}_{\text{SOFC}} + \dot{W}_{\text{MGT}} + \dot{Q}_{\text{HRSG}}}{\dot{m}_{\text{fuel,SOFC-MGT}} \cdot LHV_{\text{syngas}}} \quad (9.12)$$

$$\psi_{\text{SOFC-MGT CHP}} = \frac{\dot{W}_{\text{SOFC}} + \dot{W}_{\text{MGT}} + \dot{E}x_{\text{Q,HRSG}}}{\dot{m}_{\text{fuel,SOFC-MGT}} \cdot ex_{\text{syngas}}} \quad (9.13)$$

### ***Assumptions and Data Use***

The following assumptions are made in the analyses of the integrated SOFC-MGT system with biomass gasification:

- The system operates at steady-state.
- All gases are considered ideal.
- Heat losses to the environment from the system boundary are considered negligible.

**Table 9.1** Input parameters for the gasification system

Parameter	Value
<i>Dryer</i>	
Biomass feed rate (kg/s)	0.011 <sup>a</sup>
Superheated steam pressure (bar)	3
Superheated steam temperature (°C)	200
Moisture fraction of feed biomass (kg <sub>moisture</sub> /kg <sub>WB</sub> )	0.5 <sup>b</sup>
<i>Gasifier</i>	
Steam pressure (bar)	10 <sup>b</sup>
Steam temperature (°C)	400
Steam to carbon ratio, SC	2 <sup>b</sup>

<sup>a</sup> This flow rate is equivalent to 36 kg/hr of biomass

<sup>b</sup> Adapted from [7]

**Table 9.2** Input parameters for the SOFC system

Parameter	Value
Compressor inlet air temperature ( $T_0$ ) (°C)	25
Air compressor is entropic efficiency, %	85 <sup>a</sup>
Fuel compressor is entropic efficiency, %	87 <sup>a</sup>
Stack outlet temperature (°C)	1000 <sup>b</sup>
Activation area (cm <sup>2</sup> )	834 <sup>b</sup>
Cell current density (A/cm <sup>2</sup> )	0.350
Fuel utilization factor	0.850 <sup>b</sup>
Compressor pressure ratio, rc	9
API outlet temperature (Point 9 in Fig. 9.1) (°C)	527

<sup>a</sup> Adapted from [15]

<sup>b</sup> Adapted from [3, 12]

**Table 9.3** Input parameters for the MGT–HRSG system

Parameter	Value
<i>Micro Gas Turbine</i>	
MGT is entropic efficiency	0.93 <sup>a</sup>
Turbine inlet temperature (K)	1400
<i>Heat Recovery Steam Generator</i>	
Pinch point temperature difference (°C)	10
Outlet steam pressure (bar)	10

<sup>a</sup> Adapted from [15]

- Pressure drops along the system are considered negligible.
- Gasification takes place in equilibrium.
- The sawdust biomass has a chemical formula  $C_{4.643}H_{6.019}O_{2.368}N_{0.021}$  [14].

Tables 9.1, 9.2 and 9.3 list the input parameters for the analyses of the integrated system.

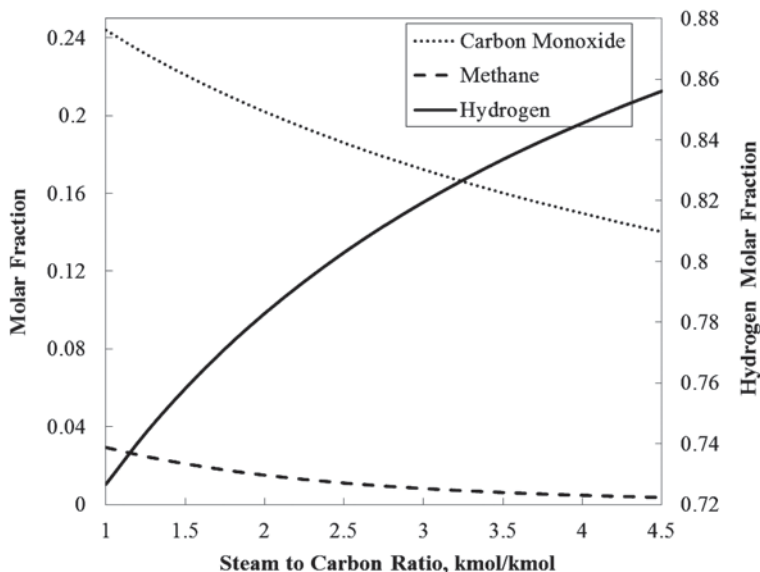


Fig. 9.2 Variation of molar fractions of syngas species with steam to carbon ratio

## 9.4 Results and Discussion

The effect of steam to carbon ratio on the syngas species molar fraction is shown in Fig. 9.2. When SC varies from 1 to 4.5 the hydrogen molar fraction increases 17.8%, while the carbon monoxide and methane molar fractions decrease by 42.5 and 87.7%, respectively. These significant changes in the molar fraction result in the variation of the total mass flow rate of the syngas with SC shown in Fig. 9.3. At SC=2, the syngas mass flow rate reaches its maximum value, after which it reduces gradually. The lower heating value of the syngas is calculated based on molar fraction of each species in the mixture. The trade-off between the variations of molar fractions with the SC results in the final variation of LHV is illustrated in Fig. 9.3.

The gasification heat requirement and exergy destruction rate are affected by the steam to carbon ratio. Introducing more steam to the gasifier decreases the need for external heat for the gasification process. The steam acts as the gasification medium and its energy content is used by the gasification process. With more steam entering the gasifier, more energy is introduced and the required heat input decreases. According to Fig. 9.4, increasing the gasification temperature results in an increase in the heat requirement of the gasifier. Although, the heat requirement of the gasifier varies significantly with the change in temperature, the gasification process exergy destruction rate does not seem to be affected noticeably. This is shown in Fig. 9.5, in which the exergy destruction rate is observed to decrease with increasing steam to carbon ratio.



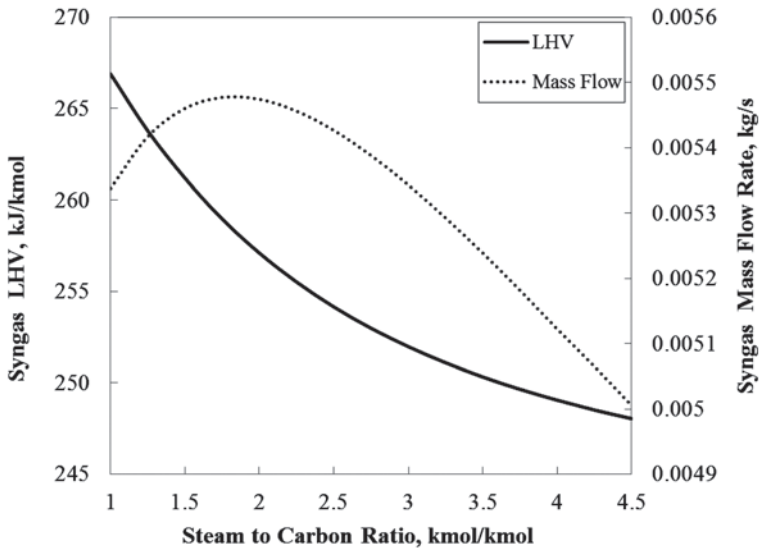


Fig. 9.3 Variation of syngas lower heating value and mass flow rate with steam to carbon ratio

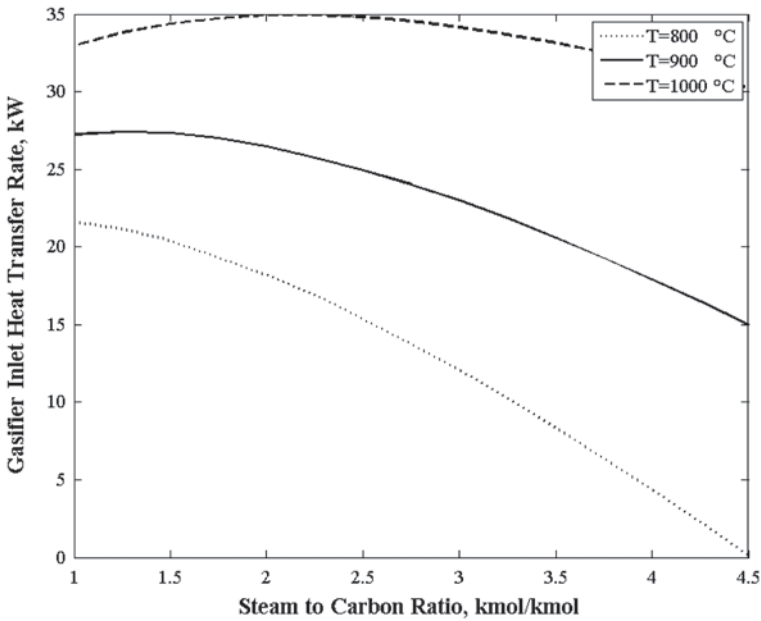
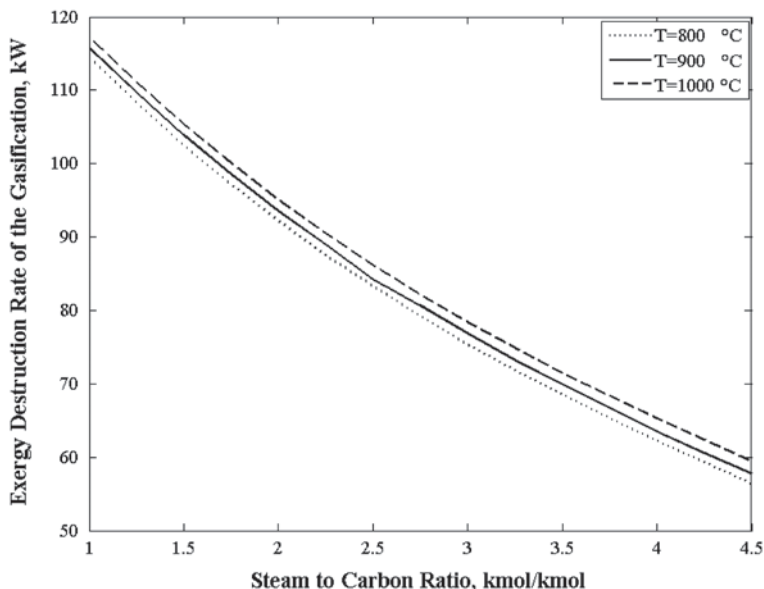


Fig. 9.4 Effect of steam to carbon ratio on the gasifier heat requirement rate for various gasification temperatures



**Fig. 9.5** Gasification exergy destruction rate vs. steam to carbon ratio for various gasifier temperatures

Energy and exergy efficiencies of biomass gasification are obtained using Eqs. 7 and 8. The variations of these efficiencies with SC and the gasifier temperature are illustrated in Figs. 9.6 and 9.7, respectively.

Fig. 9.6 shows that for a gasifier temperature of 800 °C, the total energy efficiency of the gasification process reaches its maximum value of 65.6% at SC=2. With further increase in the gasification medium into the gasifier, the energy efficiency drops, reaching 62.4% for SC=4.5. Increasing the gasification temperature reduces the total energy efficiency, as seen in Fig. 9.6. The gasification exergy efficiency exhibits a similar trend as the energy efficiency. However, the maximum value occurs at higher SC values. Higher values are achieved for efficiencies based on exergy compared to energy, because the exergy of heat is less than its energy. Since heat is an input to the gasification process, the denominator of the efficiency definition for exergy is less than that for energy.

The SOFC-MGT power output varies as a result of the change in the syngas LHV, as do the total energy and exergy efficiencies of the integrated SOFC-MGT system with biomass gasification. These variations are illustrated in Figs. 9.8 and 9.9.

According to the results in Fig. 9.2, the molar fraction of both CO and CH<sub>4</sub> decrease with increasing steam to carbon ratio. These two constituents are the source of CO<sub>2</sub> production in the SOFC-MGT cycle. However, by introducing more steam to the gasifier, the rate of CO<sub>2</sub> production increases, which results in an overall increase in the CO<sub>2</sub> emission of the integrated SOFC-MGT cycle with biomass gasification (Fig. 9.10).

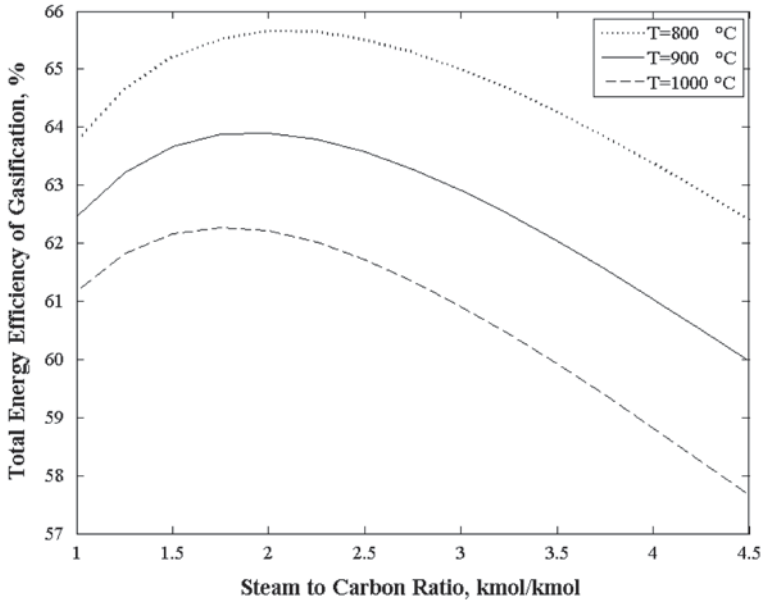


Fig. 9.6 Total energy efficiency of sawdust gasification vs. steam to carbon ratio, for various gasifier temperatures

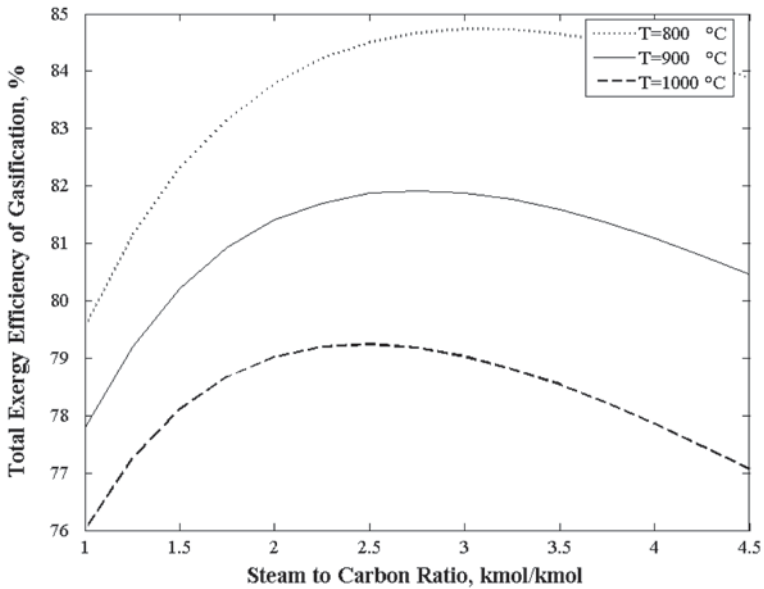


Fig. 9.7 Total exergy efficiency of sawdust gasification vs. steam to carbon ratio, for various gasifier temperatures

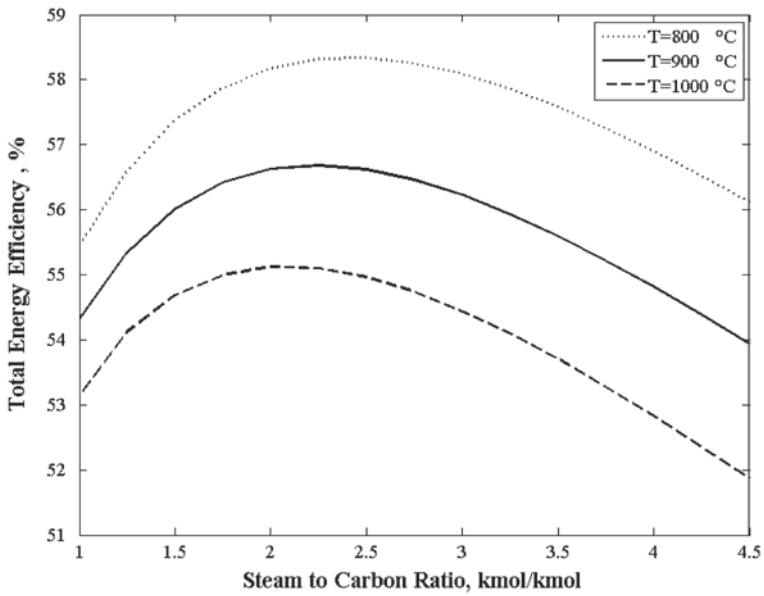


Fig. 9.8 Variation of total energy efficiency with SC for gasifier at various temperatures

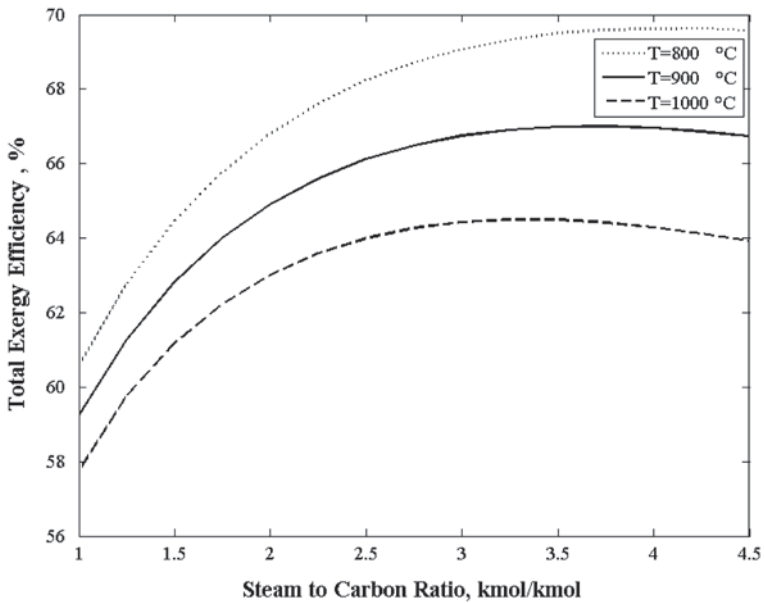


Fig. 9.9 Variation of total exergy efficiency with SC for gasifier at various temperatures

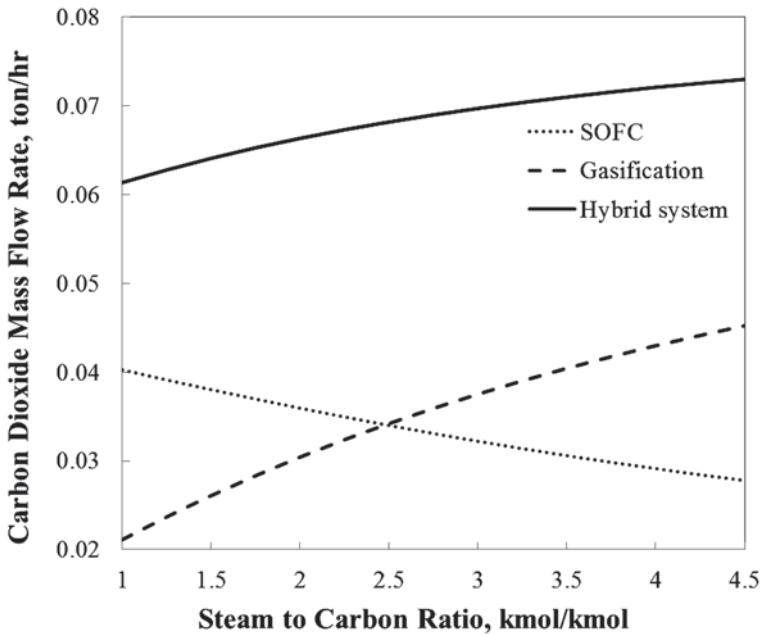


Fig. 9.10 Variation of carbon dioxide emission with steam to carbon ratio

## Conclusions

Energy and exergy analyses were performed for an SOFC-MGT cycle with biomass gasification. The integrated system performance varies by introducing more steam to the gasifier. Although the hydrogen molar fraction in the product syngas of sawdust biomass gasification increases by 17.8% with the change in steam to carbon ratio from 1 to 4.5, the carbon monoxide and methane molar fractions decrease by 42.5 and 87.7%, respectively. The gasification process is sensitive to the steam to carbon ratio of the gasifier, and the mass flow rate of the product syngas reaches its maximum value at  $SC=2$ . However, the LHV of the product syngas reduces by 7.05% when  $SC$  increases from 1.0 to 4.5. For a gasifier temperature of 800 °C, the energy efficiency of the gasification process reaches the maximum value of 65.5%, although the exergy efficiency varies slightly differently. By introducing more steam to the gasifier, the rate of  $CO_2$  production increases, which results in an overall increase in the  $CO_2$  emission of the integrated SOFC-MGT cycle with biomass gasification.

## Nomenclature

$ex$	specific exergy, kJ/kg
$\dot{Ex}$	exergy flow rate, kW
$h$	specific enthalpy, kJ/kg

$h_f$	enthalpy of formation, kJ/kmol
$i$	current density, A/cm <sup>2</sup>
$\dot{I}$	exergy destruction rate, kW
$LHV$	lower heating value, kJ/kg
$\dot{m}$	mass flow rate, kg/s
$n$	reaction coefficient
$\dot{n}$	molar flow rate, kmol/s
$N$	number of cells in the SOFC
$\dot{Q}$	heat flow rate, kW
$rc$	compression ratio
$SC$	steam to carbon ratio
$T$	temperature, °C
$\dot{W}$	electric power, kW

### Greek Letters

$\eta$	energy efficiency, %
$\psi$	exergy efficiency, %
$\gamma$	specific heat ratio

### Subscripts

0	ambient or standard condition
$a$	air
$c$	compressor
$cell$	SOFC cell
$ex$	exergy
$g$	gas
$i$	species
$ic$	compressor inlet
$mb$	moist biomass
$MGT$	micro-gas turbine
$oc$	compressor outlet
$oMGT$	MGT outlet
$DH$	district heating heat demand
$p$	product gas
$Q$	heat
$s$	surface or steam
$TIT$	turbine inlet temperature
WB	wet biomass

### Superscripts

*	reference condition
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## Acronyms

SOFC	solid oxide fuel cell
MGT	micro gas turbine
HRSG	heat recovery steam generator

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