

Performance Assessment of a Steam Gasification-Based Hybrid Cogeneration System



Sk Arafat Zaman, Dibyendu Roy, and Sudip Ghosh

Abstract In this article, a hybrid cogeneration scheme based on a solid oxide fuel cell (SOFC)—gas turbine system and utilizing syngas derived from municipal solid wastes (MSW)—has been investigated thermodynamically. Steam gasification of municipal solid wastes produces hydrogen-rich gas that is consumed by the SOFC stack as fuel. An externally fired air turbine (EFAT) draws the heat of combustion of the SOFC exhaust via a heat exchanger, while the clean turbine exhaust air itself is fed to the cathode of the SOFC. A bottoming heat recovery steam generator (HRSG) further recovers waste heat to produce process steam required for the gasifier as well as for process heater. Results of the study for base case parameters show that the integrated system can have a maximum electrical efficiency of about 50%, while substantial fuel saving (more than 51% when compared with separate power and steam plants) because of cogeneration of steam required for gasification system.

Keywords SOFC · Steam gasification · Gas turbine · MSW

1 Introduction

Municipal solid waste (MSW) is considered as one of the most favorable forms of renewable sources, and currently, it has emerged as a preferable choice for fossil fuel alternative. Alarming situation of environmental condition across the globe is the reason for growing interest of renewable power plant with higher efficiency with lower environmental impact. Solid oxide fuel cell (SOFC) which operates at very high-temperature (600–1000 °C) [1] is an ideal alternative to conventional power generation plant. Lesser CO₂ emission and higher efficiency make high-temperature fuel cells more appealing as a power generating unit [2]. Different SOFC-based systems were modelled and investigated by previous researchers. Roy et al. [2] investigated a biomass-based SOFC-externally fired gas turbine-organic Rankine

S. A. Zaman · D. Roy · S. Ghosh (✉)

Department of Mechanical Engineering, Indian Institute of Engineering Science and Technology, Shibpur, Howrah, West Bengal 711103, India

e-mail: sudipghosh.becollege@gmail.com

© Springer Nature Singapore Pte Ltd. 2021

S. Revankar et al. (eds.), *Proceedings of International Conference*

on Thermofluids, Lecture Notes in Mechanical Engineering,

https://doi.org/10.1007/978-981-15-7831-1_27

cycle (ORC) integrated system and it was observed that the highest efficiency of the system near 50%. Mishra et al. [3] investigated a reversible solid oxide fuel cell (RSOFC) plant integrated with solar PV/T and they reported highest efficiency to be 77%. Ghosh et al. [4] investigated proton-conducting RSOFC integrated solar thermal power plant and they found that maximum efficiency around 65% at cell operation temperature 873 K and current density of 500 A/m². Wang et al. [5] investigated integration of SOFC with process utility plant and they reported the improvement in efficiency and reduction in emission as fuel cell is added to industries. Biomass gasification-based modelling and analyzing have been done before by previous researchers. Pilatau et al. [6] investigated performance of an integrated gasification combined cycle (IGCC) plant coupled with diesel engine and they found the possibility of CO₂ exhaust reduction to atmosphere by 1.5 times in combined cycle system with biomass gasifier. Matelli [7] investigated performance assessment of a biomass-based cogeneration system in which he used a shell for quick prototyping. Pande et al. [8] performed experimental and numerical analyses for designing two-pot biomass cookstove and they found that combined mathematical and computational helps designing cookstove. Keche et al. [9] simulated air gasification process employing ASPEN PLUS software and they reported higher conversion efficiency with babul wood. Cebucean et al. [10] investigated the performance assessment of coal-based power systems co-fired with biomass and they reported negative values of CO₂ exhaust capturing carbon from the plant. Rivera-Tinoco and Bouallou [11] investigated biomass incineration process related to CO₂ emissions and reduction of 135 Mt of carbon was observed to produce hydrogen using steam methane reforming.

In this paper, preliminary thermodynamic assessment of a steam gasification-based SOFC-externally fired air turbine (EFAT) integrated cogeneration plant has been carried out. Syngas is produced from municipal solid wastes and power is generated utilizing a SOFC and EFAT module. Required steam for steam gasification is obtained by utilizing the heat content of outlet gas stream using a HRSG, from where we also get additional process heat.

2 Model Description

The simplified flow diagram of the proposed system is shown in Fig. 1. The integrated system mainly consists of two subunits: steam gasification unit and power generation unit.

Municipal waste management (MSWM) system is used to pre-process the MSW before feeding it to the gasifier. MSWM encompasses production, storage, gathering, transfer, transport, processing, and disposal sequentially. A detailed discussion of MSWM system can be found in the work of Das and Bhattacharyya [12].

MSW is fed to the gasifier unit after being processed by the MSWM system. H₂-rich syngas is obtained from the steam gasification unit, which is then fed to the anode of the SOFC after being processed and conditioned at the high-temperature gas cleaning unit. Syngas is heated to the required inlet temperature of SOFC by a

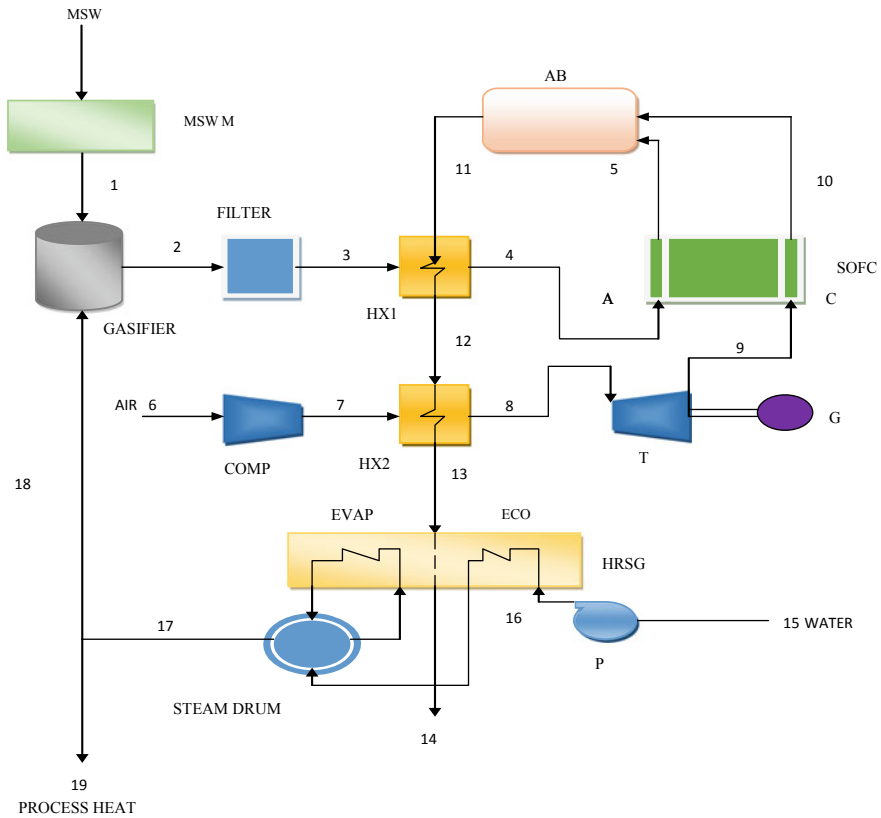


Fig. 1 Schematic of MSW-based SOFC-EFAT cogeneration plant

heat exchanger (HX1). Air is compressed and is preheated through heat exchanger (HX2), which then drives an air turbine and then is fed to the cathode of SOFC. The combustible outlet gases from the anode channel and the unutilized air from cathode outlet are fed to an afterburner (AB). The gas stream departing the after burner is passed through both heat exchangers HX1 and HX2, respectively. And finally, a HRSG utilizes the heat content of the gas stream from where steam for gasification and process heat is generated.

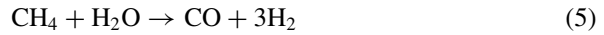
3 Thermodynamic Modeling and Analysis

The composition of biomass used (municipal solid wastes) is shown in Table 1

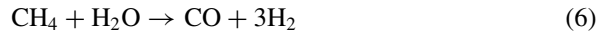
Thermodynamic equilibrium model is used in steam gasification. The major chemical reactions considered in the steam gasification process are as shown below [13]

Table 1 Composition of MSW [13]

Parameters	Value	Unit	Parameters	Value	Unit
Ultimate analysis			Proximate analysis		
C	30.77	%	FC	7.70	%
O	17.30	%	VM	46.15	%
H	4.62	%	LHV	13.31	MJ/kg
S	0.39	%	–	–	–
N	0.77	%	–	–	–
ASH	46.15	%	ASH	46.15	%



SOFC considered for this analysis is of internal reforming type. The reactions which take place are as shown below [14]



The reversible cell voltage is calculated employing Nernst equation as in Eq. (9).

$$V_N = -\frac{\Delta g}{2F} - \frac{RT}{2F} \ln \frac{P_{H_2O}}{P_{H_2} P_{O_2}^{0.5}} \quad (9)$$

The actual cell voltage (V_{act}) is obtained by deducting the total polarization losses from the reversible voltage as shown in Eq. (10)

$$V_{act} = V_N - V_{loss} \quad (10)$$

The equations to calculate different voltage losses can be found in [14]

Total power generated at the SOFC unit (or array) is estimated as Eq. (11)

$$P_{\text{SOFC}} = N_{\text{cell}} * V_{\text{act}} * i_{\text{cell}} * N_{\text{stack}} \quad (11)$$

where

N_{Stack} Total number of stacks.

N_{cell} Total number of cells.

Auxiliary power required by the pump is calculated as shown in Eq. (12).

$$P_{\text{pump}} = m_{\text{water}} * (h_{16} - h_{15}) \quad (12)$$

Power generation from the air turbine is computed using Eq. (13).

$$P_{\text{T}} = m_{\text{air}} * (h_8 - h_9) \quad (13)$$

Auxiliary power required by the air compressor is given by Eq. (14) as shown below.

$$P_{\text{COMP}} = m_{\text{air}} * (h_7 - h_6) \quad (14)$$

The total power output from plant generated is computed by Eq. (15).

$$P_{\text{net}} = P_{\text{SOFC}} + P_{\text{T}} - P_{\text{COMP}} - P_{\text{pump}} \quad (15)$$

System electrical efficiency can be obtained as shown below employing Eq. (16).

$$\eta_{\text{elec}} = \frac{P_{\text{net}}}{(m_{\text{b}} * \text{LHV}_{\text{b}}) + (m_{\text{steam}} * \text{LHV}_{\text{steam}})} \quad (16)$$

where m_{b} and m_{steam} are the mass flow rate of biomass and steam, respectively; LHV_{b} , $\text{LHV}_{\text{steam}}$ are the lower heating values of biomass and steam, respectively

Total process heat is computed employing Eq. (17).

$$Q_{\text{heat}} = m_{19} * h_{19} \quad (17)$$

The fuel energy saving ratio (FESR) when compared with separate power and steam plants is estimated as shown below [15] using Eq. (18).

$$\text{FESR} = \frac{\Delta F}{\frac{P_{\text{net}}}{\eta_{\text{e}}} + \frac{Q_{\text{heat}}}{\eta_{\text{b}}}} \quad (18)$$

where

$$\Delta F = \frac{P_{\text{net}}}{\eta_e} + \frac{Q_{\text{heat}}}{\eta_b} - (m_b * \text{LHV}_b) \tag{19}$$

where η_e and η_b are the efficiencies of the standard power system and boiler plant which are assumed to be 40% and 90%, respectively [15].

4 Results and Discussion

The volume concentration on dry basis of syngas produced after steam gasification is shown in Table 2

The base case input parameters employed are given in Table 3

In this segment, the effect of main operating and designing plant parameter, viz. current density of solid oxide fuel cell and pressure ratio of compressor on plant performance has been discussed.

Obtained results from the system under base case configurations are given in Table 4

Figure 2 shows the variation of current density on voltage and power density of SOFC. It can be observed that power density of SOFC first increases and then decreases after 7000 A/m² with the increase in current density and voltage output

Table 2 Composition of syngas components

Components	Volume concentration (%)	Components	Volume concentration (%)
CO	23.92	N ₂	0.24
CO ₂	21.07	CH ₄	0.03
H ₂	54.74	–	–

Table 3 Base case input parameters for the system [14]

Parameters	Value	Parameters	Value
Current density of (A/m ²)	2000	Gasification temperature (°C)	800
Cell area (A _{cell}) (m ²)	0.01	S/B	1
SOFC operating temperature (°C)	850	Number of cells (N _{cell})	500
Fuel utilization ratio of SOFC	0.80	Number of stacks (N _{stack})	20
Oxygen utilization ratio of SOFC	0.17	Pressure ratio of compressor	1.6
		–	–

Table 4 Base case performance indicators

Parameters	Value	Parameters	Value
P _{net} (kW)	176.62	Electrical efficiency (%)	47.70
Q _{heat} (kW)	162.64	FESR (%)	50.27

from SOFC decreases with the rise in current density. Operating voltage of SOFC decreases with the rise in current density as the voltage polarization losses also with the rise in current density. And the power density increases with the rise in current density because more syngas is drawn by the anode of SOFC as current density increases, which results in increased SOFC power output.

Figure 3 shows the effect of current density on process heat output and net power output. The process heat output of the system increases linearly with the rise in current density of SOFC from 1000 to 9000 A/m² and the net power output increases in a nonlinear fashion [2, 16] as shown in Fig. 3. The compressor power also increases as current density increases. But the combined effect of SOFC and GT power increase is much more than compressor power increase. The range of net power output obtained is 93.5–406.47 kW and the range of process heat output obtained is 80.62–729.88 kW.

Figure 4 shows the variation of electrical efficiency and fuel energy saving ratio of the system with varying current density of SOFC for a constant pressure ratio of compressor. It is observed that both electrical efficiency and FESR decreases in a similar manner with the increase in current density. This is because though the net

Fig. 2 Effect of current density of SOFC on voltage and power density of SOFC

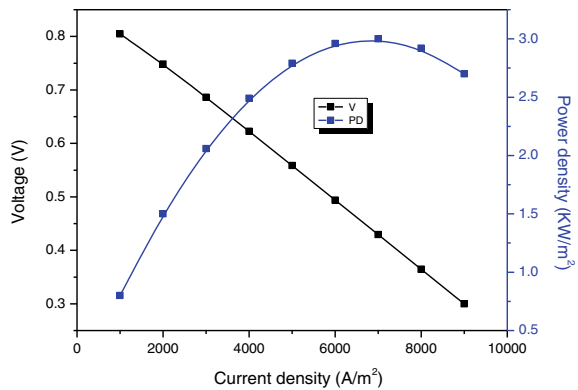


Fig. 3 Effect of current density of SOFC on net power of plant and process heat

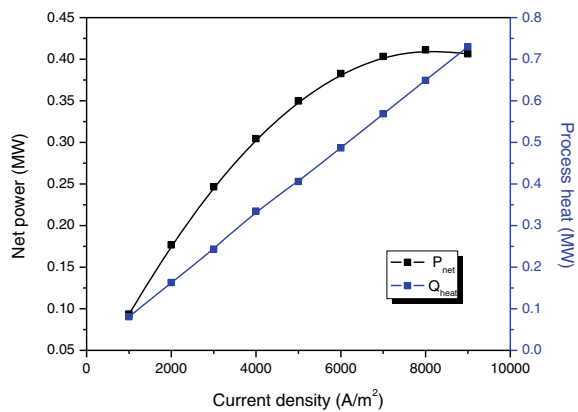
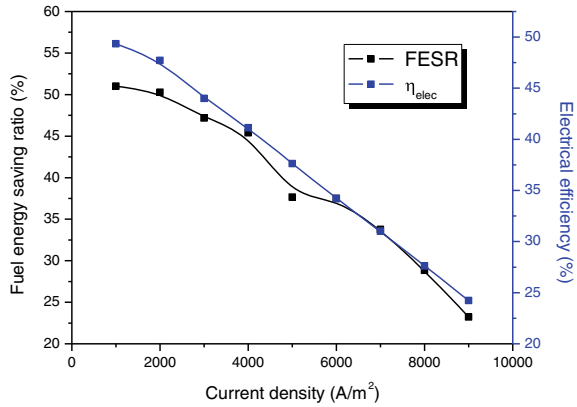


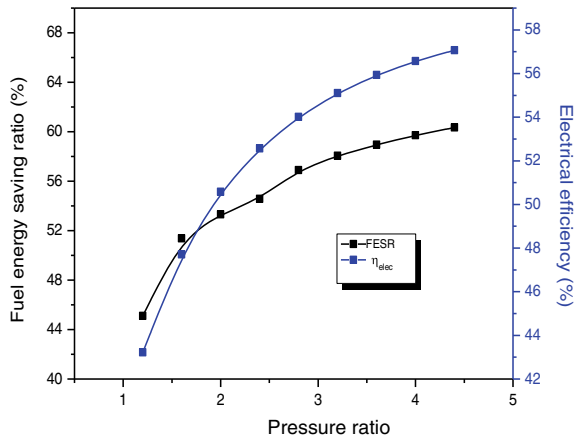
Fig. 4 Impact of SOFC current density on FESR and electrical efficiency of plant



output power increases with the increase in current density, the energy input to the system in the form of biomass and steam increases as their mass flow rate increases with the rise in current density. The electrical efficiency obtained for the system is in the range of 24.22–49.34% and FESR obtained is in the range of 23.22–51.01%.

Figure 5 shows the effect of pressure ratio of compressor on FESR and electrical efficiency for a constant current density. Compression ratio beyond 4.4 has not been taken into account as it results in lower cathode channel temperature of air [17]. As pressure ratio increases, both FESR and electrical efficiency increases. The reason for this is as pressure ratio increases, net power and process heat output from the system increase, leading to increase in both electrical efficiency and FESR.

Fig. 5 Influence of pressure ratio of compressor on FESR and electrical efficiency of plant



5 Conclusion

Thermodynamic study of a hybrid cogeneration system based on a solid oxide fuel cell (SOFC)—gas turbine system and utilizing syngas produced from municipal solid wastes (MSW)—has been carried out. The influence of major operating parameters is examined on performance parameters of the plant. The main findings are as shown below

- At higher current density, the values of both process heat output and net power output increase and their maximum values are 729.88 kW and 406.47 kW, respectively.
- At elevated levels of current density, the values of electrical efficiency and fuel energy saving ratio decrease and their maximum values are found to be 49.34% and 51.01%, respectively.
- As current density of SOFC increases, power density of SOFC increases for a while and then decreases and voltage output from SOFC decreases linearly and their maximum values are 2.7 and 0.8045, respectively.
- With the rise of pressure ratio, both electrical efficiency and FESR increase in a similar manner for a constant current density and their maximum values are 57.07% and 60.35%, respectively.

References

1. Rangel-Hernández VH, Fang Q, Blum L, Ramírez-Minguela JJ, Zaleta-Aguilar A (2019) Impact of operational and design variables on the thermodynamic behavior of a simulated 500 kw ng-fueled solid oxide fuel cell stack. *Energy Convers Manag* 204:112283. <https://doi.org/10.1016/j.enconman.2019.112283>
2. Roy D, Samanta S, Ghosh S (2019) Techno-economic and environmental analyses of a biomass based system employing solid oxide fuel cell, externally fired gas turbine and organic Rankine cycle. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2019.03.261>
3. Mishra AK, Roy D, Ghosh S (2018) Reversible solid oxide fuel cell connected to solar PV/T system: cell electrochemical modelling and analysis. *IOP Conf Ser Mater Sci Eng* 377:0–6 (2018). <https://doi.org/10.1088/1757-899X/377/1/012077>
4. Ghosh A, Roy D, Ghosh S (2019) Proton conducting reversible SOFC integrated in a solar thermal power generation system. *J Phys Conf Ser* 1240. <https://doi.org/10.1088/1742-6596/1240/1/012112>
5. Wang B, Zhang N, Hwang S, Kim J (2013) Process integration of solid oxide fuel cells with process utility systems. *Clean Techn Environ Policy* 15(5):801–815. <https://doi.org/10.1007/s10098-013-0643-1>.
6. Pilatau AY, Viarshyna HA, Gorbunov AV, Nozhenko OS, Maciel HS, Baranov VY, Mucha OV, Maurao R, Lacava PT, Liapshko I, Filho GP, Matus A (2014) Analysis of syngas formation and ecological efficiency for the system of treating biomass waste and other solid fuels with CO₂ recuperation based on integrated gasification combined cycle with diesel engine. *J Braz Soc Mech Sci Eng* 36(4):673–679. <https://doi.org/10.1007/s40430-014-0166-7>.
7. Matelli JA (2016) Conceptual design of biomass-fired cogeneration plant through a knowledge-based system. *J Braz Soc Mech Sci Eng* 38:535–549. <https://doi.org/10.1007/s40430-015-0326-4>

8. Pande RR, Sharma SK, Kalamkar VR (2019) Experimental and numerical analyses for designing two-pot biomass cookstove. *J Braz Soc Mech Sci Eng* 41:1–18. <https://doi.org/10.1007/s40430-019-1839-z>
9. Keche AJ, Prasad A, Gaddale R (2015) Simulation of biomass gasification in downdraft gasifier for different biomass fuels using ASPEN PLUS. *Clean Technol Environ Policy* 17:465–473. <https://doi.org/10.1007/s10098-014-0804-x>
10. Cebrucean D, Cebrucean V, Ionel I (2019) Modeling and performance analysis of subcritical and supercritical coal-fired power plants with biomass co-firing and CO₂ capture. *Clean Technol Environ Policy*. <https://doi.org/10.1007/s10098-019-01774-1>
11. Rivera-Tinoco R, Bouallou C (2010) Using biomass as an energy source with low CO₂ emissions. *Clean Technol Environ Policy* 12:171–175. <https://doi.org/10.1007/s10098-009-0241-4>
12. Das S, Bhattacharyya BK (2015) Performance evaluation of the proposed and existing waste management system: economic analysis. In: Proceedings of the 2015 international conference on Operations Excellence and Service Engineering. Orlando, Florida, USA, pp 267–277.
13. Pala LPR, Wang Q, Kolb G, Hessel V (2017) Steam gasification of biomass with subsequent syngas adjustment using shift reaction for syngas production: An Aspen plus model. *Renew Energy* 101:484–492. <https://doi.org/10.1016/j.renene.2016.08.069>
14. Roy D, Samanta S, Ghosh S (2019) Energetic and exergetic analyses of a solid oxide fuel cell (SOFC) module coupled with an organic rankine cycle. In: Saha P, Subbarao P, Sikarwar B (eds) *Advances in fluid and thermal engineering*. Lecture notes in mechanical engineering. Springer, Singapore
15. Ghosh S, De S (2006) Energy analysis of a cogeneration plant using coal gasification and solid oxide fuel cell. *Int J Energy Res* 31:345–363. <https://doi.org/10.1016/j.energy.2005.01.011>
16. Lin Y, Beale SB (2006) Performance predictions in solid oxide fuel cells. *Appl Math Model* 30:1485–1496. <https://doi.org/10.1016/j.apm.2006.03.009>
17. Roy D, Samanta S, Ghosh S (2018) Thermodynamic analysis of a biomass based solid oxide fuel cell integrated advanced power generation system. *IOP Conf Ser Mater Sci Eng* 377. <https://doi.org/10.1088/1757-899X/377/1/012210>.