Thermodynamic analysis of a biomass based solid oxide fuel cell integrated advanced power generation system

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Abstract. In this paper, thermodynamic analysis of a biomass based advanced power generation system has been performed. The proposed system is a combination of a biomass gasifier with gas cleaning unit, a solid oxide fuel cell module, an indirectly heated air turbine and a supercritical CO₂ power cycle with two stage compression and intercooling. Parametric analysis has been carried out to investigate the influences of major plant parameters, such as, the current density of fuel cell and the air turbine pressure ratio, on power output and overall plant efficiency. The results show that the proposed system can yield overall efficiency in the range of 30-55%.

1. Introduction

Energy requirement in the form of electricity can rise up to 30-35% in the next 30 years, according to IEA statistics [1]. Meeting this goal with conventional fossil power generation technology will create severe negative effect on environment. Hence, attentions are given to developing new and renewable resource based power generation systems. In this context, biomass energy powered fuel cell system can provide clean, renewable and sustainable form of energy. Biomass is considered as an alternate to fossil fuel due to its carbon neutrality. It can be converted to hydrogen-rich producer gas by either air or steam-gasification process. Extensive cleaning of producer gas is important for end use, as impurities viz. tars, particulate matters are generated during gasification process. Biomass based technology is more or less mature and it has a huge potential to integrate with fuel cell devices. Fuel cells are devices which have the potential to convert chemical energy stored in fuel to electricity. Integration of biomass gasification technology with high temperature fuel cell such as solid oxide fuel cell (SOFC) is advantageous than other type of fuel cell because of its operating temperature which is close to gasification temperature. Hydrogen rich producer gas, derived from the gasifier, can be utilized for producing electrical power by feeding it to the anode of SOFC. CO₂ based power cycles can also be integrated as a bottoming cycle for efficient energy recovery from a low or medium waste heat source.

Several studies on solid oxide fuel cell integrated combined system have been reported in the literature. Nagel et al. [2] investigated the feasibility of integration of biomass gasification with high-temperature solid oxide fuel cells. Meng et al. [3] analysed the performance of methane fuelled SOFC/GT and transcritical CO₂ cycle integrated power generation system. A performance study of a
coal gasification-based SOFC integrated combined heat and power plant have been reported by Ghosh and De [4]. Yan et al. [5] studied the performance of an integrated power system employing an SOFC-GT system with an ORC. Roy and Ghosh [6] performed energetic and exergetic analyses of a biomass gasification based SOFC-GT-ORC power generation system. Mahmoudi and Khani [7] studied a power generation system employing methane-fuelled SOFC-GT cycle and a pressurized warm water generation. Mondal and De [8] studied the performance of a s-CO$_2$ power cycle with multistage compression and intercooling for low temperature waste heat recovery. Aravind et al.[9] studied different gas cleaning approaches for gasifier and SOFC integration.

In this paper, an advanced power generation system consisting of a biomass gasifier with gas cleaning unit, a solid oxide fuel cell module, an indirect heated air turbine and a supercritical CO$_2$ power cycle with two stage compression and intercooling has been proposed. The energetic performance of the integrated system has been investigated under varying different design and operating conditions.

![Schematic of proposed power generation system](image)

**Figure 1.** Schematic of proposed power generation system.

### 2. System description and assumption

Schematic representation of the proposed system is shown in figure 1. It is comprised of a biomass gasifier with gas cleaning unit, a solid oxide fuel cell module, an indirectly heated air turbine and a supercritical CO$_2$ power cycle with two stage compression and intercooling. Compressed air is fed by an air compressor (AC1) to the downdraft biomass gasifier for the gasification of the woody biomass. Producer gas, derived from gasifier, is fed to the anode of SOFC after extensive cleaning of the producer gas in the gas cleaning unit (GCU). On the other hand, hot and recirculated exhaust air from the air turbine is fed to the cathode of SOFC. Unutilised fuel coming out from anode is completely burned in the after burner (AB) unit by utilizing cathode fed air. Flue gas from the AB exhaust is used to heat up the incoming anode channel producer gas. Compressed air by AC2 enters a heat exchanger (HEX2) unit and heated up. Hot and compressed air is then expanded in an air turbine (AT). Waste heat from the heat recovery gas heater (HRGH) is used to run a s-CO$_2$ power cycle, where CO$_2$ expands in the gas turbine (GT) to produce additional power.
Following assumptions have been considered for the simulation purpose.

- Reference environmental condition are $P_o=101.325$ kPa, $T_o=298.15$ K.
- Air consists of 79% N$_2$ and 21% O$_2$ by volume basis.
- Tar compounds and char formation are not considered in the gasifier.
- All gases are assumed to be ideal gas.
- Fuel cell stack is entirely insulated.
- Anode and cathode exit channels of SOFC have same temperature.

3. System modelling and analysis

A downdraft gasifier has been considered for the proposed system. Woody biomass feedstock with representative chemical formula $CH_mN_nO_o$ is fed as a fuel to the gasifier. The reactions considered to be taken place in the reduction zone are methanation and water-gas shift reaction [10].

$$C + 2H_2 \leftrightarrow CH_4 \quad \text{(methanation reaction)}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \text{(water gas shift reaction)}$$

Global gasification reaction for biomass fuel is written below (Zainal et al. 2001)

$$CH_mN_nO_o + X_mH_2O + X_0(O_2 + 3.76N_2) = X_{H_2}H_2 + X_{CO}CO + X_{CO_2}CO_2 + X_{H_2O}H_2O + X_{CH_4}CH_4 + X_{N_2}N_2$$

where $X_m$ represents the number of kmoles of moisture per kmole of biomass, $X_o$ denotes the number of kmoles of oxygen per kmole of fuel, and the coefficients $X_{H_2}$, $X_{CO}$, $X_{CO_2}$, $X_{H_2O}$, $X_{CH_4}$ and $X_{N_2}$ denote the moles of respective constituents of producer gas.

Internal reforming type SOFC has been selected for the proposed system. The simultaneous reactions assumed to be taken place inside the SOFC are steam reforming, water-gas shift and electrochemical respectively.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \text{(steam reforming)}$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \quad \text{(water-gas shift)}$$

$$H_2 + 0.5O_2 \leftrightarrow H_2O \quad \text{(electrochemical)}$$

Nernst equation has been utilised for the estimation of reversible cell voltage as follows

$$V_N = \frac{-\Delta G^o}{2F} - \frac{RT_{cell}}{2F} \ln \left( \frac{p_{H_2O}}{p_{H_2}p_{O_2}^{0.5}} \right)$$

Cell voltage ($V_c$) is estimated by subtracting the total voltage losses from the Nernst voltage. It is expressed as

$$V_c = V_N - V_{Loss}$$

Total voltage loss developed in the SOFC cell is the combination of ohmic losses, activation and concentration losses

$$V_{Loss} = V_{Ohmic} + V_{Activation} + V_{Concentration}$$

The voltage losses are estimated by different correlations as described by Roy and Ghosh [6]

Current flow through a single SOFC cell is calculated as follows

$$i_{cell} = j \cdot A_{cell}$$

Power generated in a single SOFC stack has been estimated as follows

$$W_{stack} = N_{cell} \cdot i_{cell} \cdot V_{cell}$$

Power obtained from the SOFC module is estimated as follows

$$W_{SOFC} = N_{SOFC} \cdot W_{stack}$$

where, $N_{cell}$ is the number of cells in a SOFC stack

$N_{SOFC}$ is the total number of stacks in the SOFC module

Pressure ratio of AT is defined as follows
\[ R_{P_{AT}} = \left( \frac{T_{AT,\text{out}}}{T_{AT,\text{in}}} \right) \]  

Power obtained from AT block is estimated as follows
\[ W_{AT} = m_{\text{air}} \left( h_{AT,\text{in}} - h_{AT,\text{out}} \right) \]  

Power obtained from GT is calculated as follows
\[ W_{GT} = m_{\text{air}} \left( h_{GT,\text{in}} - h_{GT,\text{out}} \right) \]  

### 4. Performance parameters

The total power developed from the system is estimated as
\[ W_{\text{sys}} = W_{\text{SOFC}} + W_{\text{AT}} + W_{\text{GT}} - W_{\text{Aux}} \]  

where \( W_{\text{Aux}} \) represents auxiliary power consumption and is estimated as follows
\[ W_{\text{Aux}} = W_{\text{AC1}} + W_{\text{AC2}} + W_{\text{LPC}} + W_{\text{HPC}} \]  

The net efficiency of the proposed power generation system is expressed as
\[ \eta_{\text{net}} = \frac{W_{\text{net}}}{n_{\text{LHV, biomass}}} \]  

### Table 1. Base case input parameters

| Parameter                          | Ref. | Value         | Parameter                          | Ref. | Value         |
|------------------------------------|------|---------------|------------------------------------|------|---------------|
| Gasifier operating pressure        | -    | 1.06 bar      | SOFC oxygen utilization factor     | -    | 0.17          |
| Gasifier operating temperature    | [15] | 1073 K        | SOFC fuel utilization factor       | [12] | 0.80          |
| Moisture content of biomass       |      | 20%           | Number of cells in a stack         | -    | 500           |
|                                   |      |               | Number of stack in SOFC module     | -    | 600           |
| Biomass composition               | [16] | C=50.6%       | Pressure drop in SOFC              | -    | 1%            |
|                                   |      | H=6.5         | Pressure drop in AB                | -    | 1%            |
|                                   |      | O=42%         | AT pressure ratio                  | -    | 1.6           |
|                                   |      | N=0.2%        | Isentropic efficiency of compressor| [14] | 85%           |
|                                   |      | Ash=0.7%      | Isentropic efficiency of air turbine| -    | 90%           |
| Pressure drop in gasifier         | -    | 1%            | Minimum terminal temperature difference in RH | [8]  | 8 K           |
| GCE exit temperature              | -    | 923 K         | Pinch point temperature of HRGH    | [8]  | 20 K          |
| GCE pressure drop                 | [13] | 1%            | GT inlet pressure                  | -    | 120 bar       |
| SOFC operating temperature        | -    | 1123 K        | GT inlet temperature               | -    | 523 K         |
| SOFC current density              | -    | 2000          | CO\text{2} power cycle intermediate pressure | [8]  | 80 bar       |
| Cell area (A\text{cell})          | [14] | 0.01 m\text{2} | CO\text{2} power cycle lowest pressure | [8]  | 60 bar       |
5. Results and discussion

All the input parameters, used for the simulation of the plant, are given in table 1. Base case performance of the proposed system is shown in table 2. Performance of the proposed system is greatly dependent on current density of fuel cell and pressure ratio of air turbine. Influence of these parameters on the performance of the proposed system has been investigated in the following sections.

Effect of SOFC current density on power and efficiency have been shown in figure 2 and figure 3, respectively. It is seen that as the current density increases, power output from all the power producing devices i.e. SOFC, AT and GT increases. Thus, net power output of the system also increases. As the current density of the SOFC increases, fuel consumption of the gasifier unit also increases, which in turn increases producer gas production. Higher amount of producer gas consumption at the SOFC module leads to higher power output from SOFC module. On the other hand, higher fuel consumption results in higher amount of oxygen requirement in the SOFC unit. That results in higher amount of air consumption by AC2 unit and subsequently expansion in AT. Thus, power output from AT increases. Again, increase of fuel and air consumption in the SOFC unit results in higher molar flow rate of flue gas. It results in higher amount of heat recovery in the HRGH unit. Thus, power output from GT also increases. Higher current density results in rise of polarisation losses in the SOFC unit. It results in lower cell voltage. Drop of energetic efficiency of the system is highly attributed to the decrease in cell voltage. Thus, as the current density increases, energetic efficiency of the system also decreases.

| Table 2. Base case performance |
| Parameter | Value | Unit |
| --- | --- | --- |
| \( V_C \) | 0.768 | V |
| \( W_{\text{Stack}} \) | 7.37 | kW |
| \( W_{\text{SOFC}} \) | 4424 | kW |
| \( W_{\text{AT}} \) | 1430 | kW |
| \( W_{\text{GT}} \) | 897 | kW |
| \( W_{\text{Aux}} \) | 1050 | kW |
| \( W_{\text{sys}} \) | 5701 | kW |
| \( \eta_{\text{sys}} \) | 43.66 | % |

Figure 2. Effect of SOFC current density on power.

Figure 3. Effect of SOFC current density on efficiency and cell voltage.

Figure 4 depicts the effect of \( R_{P_{\text{AT}}} \) on individual power producing blocks at \( j=2000 \, \text{A/m}^2 \), \( T_{\text{cell}}=1123 \, \text{K} \). The effect of \( R_{P_{\text{AT}}} \) on overall system efficiency and \( W_{\text{sys}} \), have been shown in figure 5. \( R_{P_{\text{AT}}} \) has been varied from 1.2-4.4. It is found that increase of \( R_{P_{\text{AT}}} \) results in increase of \( W_{\text{AT}} \) and \( W_{\text{sys}} \). Higher \( R_{P_{\text{AT}}} \) results in higher \( W_{\text{sys}} \). Thus, increase of \( R_{P_{\text{AT}}} \) results in increase of net power and overall efficiency of the system. \( R_{P_{\text{AT}}} \) beyond 4.4 has not been investigated. It is due to the fact that it
results in lower cathode channel air inlet temperature, which can adversely affect the performance of SOFC module. Lower limit of SOFC inlet temperature must be kept to maintain effective ionic conductivity of electrolyte (Yoshida and Iwai 2005 ).

**Figure 4.** Effect of $RP_{AT}$ on power

**Figure 5.** Effect of $RP_{AT}$ on overall efficiency and $W_{sys}$

6. Conclusion

In this study, an advanced power generation system comprising of a biomass gasifier with gas cleaning unit, a solid oxide fuel cell module, an indirect heated air turbine and a supercritical CO$_2$ power cycle with two stage compression and intercooling has been modelled and analysed. Parametric investigation shows that the performance of the proposed system is highly influenced by the plant parameters i.e. applied current density and $RP_{AT}$. Thermodynamic analysis reveals that the energetic efficiency of the proposed system varies in the range of 30-55%. Maximum system efficiency is obtained at $j=2000$ A/m$^2$, $T_{cell}=1123$ K and $RP_{AT}=4.4$.

References

[1] World energy statistics 2016 ISBN PDF: 978-92-64-26307-9 Print : 978-92-64-26147-1.

[2] Nagel F P, Ghosh S, Pitta C, Schildhauer T J and Biollaz S 2011 Biomass integrated gasification fuel cell systems-Concept development and experimental results *Biomass and Bioenergy* 35 354–62

[3] Meng Q, Han J, Kong L, Liu H, Zhang T and Yu Z 2016 Thermodynamic analysis of combined power generation system based on SOFC/GT and transcritical carbon dioxide cycle *Int. J. Hydrogen Energy* 2–7

[4] Ghosh S and De S 2006 Energy analysis of a cogeneration plant using coal gasification and solid oxide fuel cell *Energy* 31 345–63

[5] Yan Z, Zhao P, Wang J and Dai Y 2013 Thermodynamic analysis of an SOFC-GT-ORC integrated power system with liquefied natural gas as heat sink *Int. J. Hydrogen Energy* 38 3352–63

[6] Roy D and Ghosh S 2017 Energy and exergy analyses of an integrated biomass gasification combined cycle employing solid oxide fuel cell and organic Rankine cycle *Clean Technol. Environ. Policy* 19 1693–709

[7] Mahmoudi S M S and Khani L 2016 Thermodynamic and exergoeconomic assessments of a new solid oxide fuel cell-gas turbine cogeneration system *Energy Convers. Manag.* 123 324–37

[8] Mondal S and De S 2015 CO2 based power cycle with multi-stage compression and intercooling for low temperature waste heat recovery *Energy* 90 1132–43

[9] P. V. Aravind, M. Liu, L. Fan, E. Promes, S. Y. Giraldo and T W 2013 Biomass Gasifier–SOFC Systems. From Electrode Studies to the Development of Integrated Systems and New Applications 57 2893–901

[10] Zainal Z A, Ali R, Lean C H and Seetharamu K N 2001 Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials *Energy Convers. Manag.* 42 1499–515

[11] Yoshida H and Iwai H 2005 Thermal management in solid oxide fuel cell systems
of 5th International conference on Enhanced compact and Ultra compact heat exchangers: Science Engineering and Technology, CHE 2005-01, Hobken, NJ, USA, September 2005

[12] Massardo and Magistri 2003 Internal Reforming Solid Oxide Fuel Cell Gas Turbine Combined Cycles (IRSOFC-GT)—Part II: Exergy and Thermoeconomic Analyses J. Eng. Gas Turbines Power 125 67

[13] Morita H, Yoshioka F, Woudstra N, Hemmes K and Spliethoff H 2004 Feasibility study of wood biomass gasification/molten carbonate fuel cell power system—comparative characterization of fuel cell and gas turbine systems J. Power Sources 138 31–40

[14] Ranjbar F, Chitsaz A, Mahmoudi S M S, Khalilarya S and Rosen M A 2014 Energy and exergy assessments of a novel trigeneration system based on a solid oxide fuel cell Energy Convers. Manag. 87 318–27

[15] Jarungthammachote S and Dutta A 2007 Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier Energy 32 1660–9

[16] Jayah T H, Aye L, Fuller R J and Stewart D F 2003 Computer simulation of a downdraft wood gasifier for tea drying Biomass and Bioenergy 25 459–69