

Energetic and Exergetic Analyses of a Solid Oxide Fuel Cell (SOFC) Module Coupled with an Organic Rankine Cycle



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Abstract In this article, energetic and exergetic analyses of a natural gas-fueled solid oxide fuel cell (SOFC) and organic Rankine cycle (ORC)-integrated power generation system are presented. In the topping, SOFC cycle of the proposed power generation system, anode channel as well as cathode channel recirculation has been done. Toluene has been used as a working fluid in the ORC. Influence of major operating and design parameters, viz. current density of SOFC, cell temperature on the performance of the proposed system has been examined. Results show that maximum energetic and exergetic efficiencies of the proposed power generation are found to be 67.06 and 58.17%, respectively.

Keywords SOFC · ORC · Power plant · Energy · Exergy · Efficiency · Waste heat

1 Introduction

Conventional fossil-fired power plant yields lower efficiency and emits a huge amount of greenhouse gases. Nowadays, focus has been given on developing new and renewable power plants having higher energy efficiency with lower environmental impact. In that context, high-temperature fuel cells, viz. solid oxide fuel cell (SOFC)

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and molten carbonate fuel cell (MCFC) can be considered to be a suitable alternative to conventional coal-fired power plants specifically in small-scale distributed power generation systems. These fuel cells emit lesser carbon dioxide and exhibit higher electrical efficiency. Organic Rankine cycle (ORC) is suitable for generating power by utilizing low-temperature waste heat. The ORCs are similar to the conventional Rankine cycles having organic fluids as a working fluid. In previous years, several SOFC-integrated thermodynamic models have been developed and analyzed. Akkaya et al. [1] modeled and analyzed methane-fed tubular SOFC module exergetically. Mahmoudi and Khani [2] proposed an indirect incorporation of methane-fueled SOFC with a gas turbine cycle and a pressurized warm water generation system. Meratizaman et al. [3] proposed a methane-driven SOFC-GT power plant in the range of 11–42.9 kW for household application. Akikur et al. [4] modeled a solar powered SOFC-integrated cogeneration system. Al-Sulaiman et al. [5] studied the performance analysis of a tri-generation system driven by methane-fueled SOFC. In this paper, an attempt has been made to integrate SOFC with ORC. Methane-fueled SOFC-based power generation system with bottoming ORC has been proposed. As SOFC is the major power production component of the system, the influence of its major designing and operating parameters on thermodynamic performance of the designed power generation system have been conducted.

2 System Description

Schematic representation of the proposed system is shown in Fig. 1. It is comprised of a topping SOFC module with a bottoming ORC. In the topping SOFC cycle of the proposed system, anode channel as well as cathode channel recirculation have been done. Compressed natural gas is first heated by a heat exchanger (HEX1) and mixed with the recirculated stream before feeding to the SOFC anode channel. On the other hand, heated compressed air is supplied to the SOFC cathode channel. Due to the chemical and electrochemical reactions, chemical energy stored at the natural gas is transformed into electrical energy at the SOFC unit. After recirculation, unutilized methane from the SOFC unit is completely burned at the after burner (AB) unit. Heat exchangers, viz. HEX1 and HEX2 are used to preheat the compressed methane and air, respectively, by using the flue gas from the AB exhaust. Waste heat from the heat recovery vapor generator (HRVG) unit is utilized to operate ORC. Toluene has been selected as working fluid at the ORC.

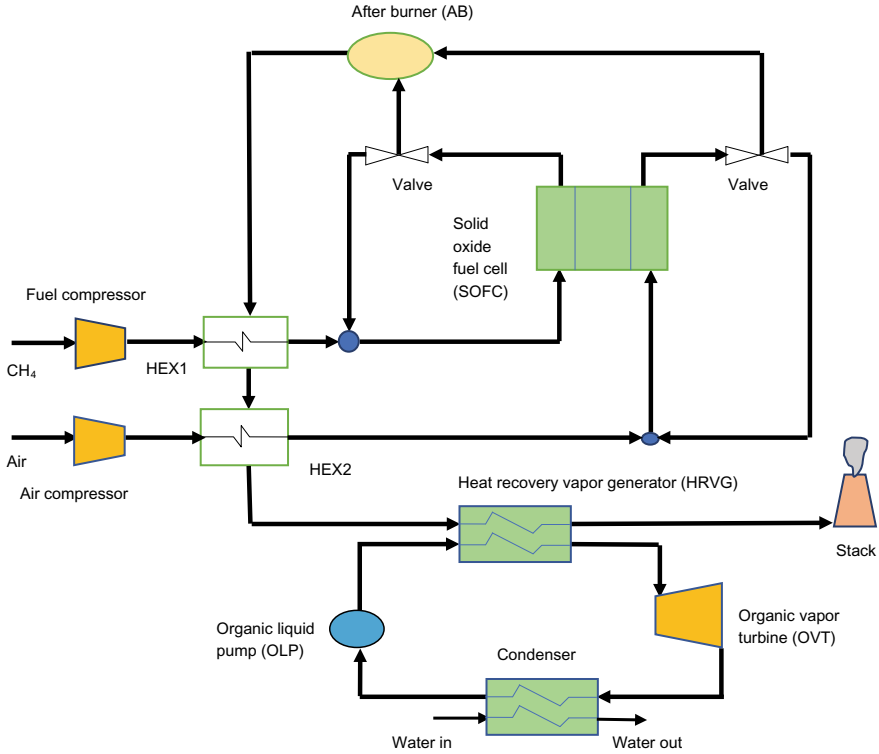
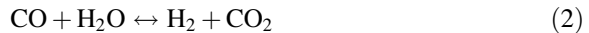
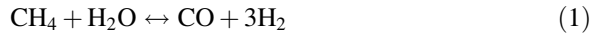


Fig. 1 Schematic of proposed system

3 Thermodynamic Modeling

SOFC considered for the system analysis is of internal reforming type. Three simultaneous reactions are supposed to be taken place, viz. steam reforming, water gas shift, and electrochemical reaction. These reactions are shown below.



Reversible cell voltage is obtained by considering Nernst equation [1]

$$V_N = -\frac{\Delta g^\circ}{2F} - \frac{RT_{\text{cell}}}{2F} \ln \left(\frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2} p_{\text{O}_2}^{0.5}} \right) \quad (4)$$

Cell voltage (V_c) is determined by deducting the total voltage losses from the Nernst voltage as follows

$$V_c = V_N - V_{\text{Loss}} \quad (5)$$

Three major voltage losses developed in the SOFC cell are ohmic loss (V_{OHM}), activation loss (V_{ACT}), and concentration loss (V_{CONC}). Total voltage losses developed in the cell are the summation of these three losses.

$$V_{\text{Loss}} = V_{\text{OHM}} + V_{\text{ACT}} + V_{\text{CONC}} \quad (6)$$

Ohmic loss is determined as follows [6]

$$V_{\text{OHM}} = (\rho_A L_A + \rho_C L_C + \rho_E L_E + \rho_{\text{INT}} L_{\text{INT}}) j \quad (7)$$

where

$$\rho_A = 0.00298 \exp\left(\frac{1392}{T_{\text{cell}}}\right) \quad (8)$$

$$\rho_C = 0.00814 \exp\left(\frac{-600}{T_{\text{cell}}}\right) \quad (9)$$

$$\rho_E = 0.00294 \exp\left(\frac{-10,350}{T_{\text{cell}}}\right) \quad (10)$$

$$\rho_{\text{INT}} = 0.1256 \exp\left(\frac{-4690}{T_{\text{cell}}}\right) \quad (11)$$

Activation over-potential is calculated as follows [7, 8]

$$V_{\text{ACT}} = V_{\text{ACT,a}} + V_{\text{ACT,c}} \quad (12)$$

$$V_{\text{ACT,a,c}} = \frac{RT_{\text{cell}}}{F} \ln \left[\frac{1}{2j_{\text{oa,oc}}} + \left\{ \left(\frac{1}{2j_{\text{oa,oc}}} \right)^2 + 1 \right\}^{0.5} \right] \quad (13)$$

$$j_{\text{oa}} = \gamma_a \frac{p_{\text{H}_2} p_{\text{H}_2\text{O}}}{p_o p_o} \exp\left(\frac{-E_{\text{act,a}}}{RT_{\text{cell}}}\right) \quad (14)$$

$$j_{\text{oc}} = \gamma_c \left(\frac{p_{\text{O}_2}}{p_o}\right)^{0.25} \exp\left(\frac{-E_{\text{act,c}}}{RT_{\text{cell}}}\right) \quad (15)$$

Concentration loss is determined as follows [9, 10]

$$V_{\text{CONC}} = V_{\text{CONC,Anode}} + V_{\text{CONC,Cathode}} \quad (16)$$

$$V_{\text{CONC,Anode}} = -\frac{RT_{\text{cell}}}{2F} \ln \left[\frac{\left(1 - \frac{j}{j_{L,H_2}}\right)}{\left(1 + \frac{j}{j_{L,H_2O}}\right)} \right] \quad (17)$$

$$V_{\text{CONC,Cathode}} = \frac{RT_{\text{cell}}}{2F} \ln \left[\frac{1}{1 - \frac{j}{j_{L,O_2}}} \right] \quad (18)$$

$$j_{L,\text{gas}} = \frac{2FD_{\text{eff,gas}}p_{\text{gas}}}{100,000RT_{\text{cell}}L_a} \quad (19)$$

Current flow during an individual cell is estimated as

$$i_{\text{cell}} = j \cdot A_{\text{cell}} \quad (20)$$

where A_{cell} represents cell area.

Power developed in a single SOFC stack is calculated as follows

$$W_{\text{Stack}} = N_{\text{cell}} V_c i_{\text{cell}} \quad (21)$$

where N_{cell} is the quantity of cells in a SOFC stack

Power achieved by the SOFC module is estimated as follows

$$W_{\text{SOFC}} = N_{\text{SOFC}} W_{\text{Stack}} \quad (22)$$

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

Power consumed by compressors is determined as follows

$$W_{\text{C1/C2}} = N_{\text{fuel/air}} (h_{\text{out}} - h_{\text{in}}) \quad (23)$$

Power consumed by organic liquid pump (OLP) is calculated as follows

$$W_{\text{OLP}} = n_{\text{ORC}} (h_{\text{out}} - h_{\text{in}}) \quad (24)$$

The power output of organic vapor turbine (OVT) is given by:

$$W_{\text{OVT}} = n_{\text{ORC}} (h_{\text{in}} - h_{\text{out}}) \quad (25)$$

4 Exergy Analysis

Exergy associated with any stream consists of physical exergy (Ex_{phy}) and chemical exergy (Ex_{che}). It is written as follows

$$Ex = Ex_{phy} + Ex_{che} \quad (26)$$

$$Ex_{phy} = \sum_j N_j ((\bar{h}_j - \bar{h}_o) - T_o(s_j - s_o)) \quad (27)$$

$$Ex_{che} = N_J \left(\sum_J y_J \bar{ex}_{che}^0 - RT_o \sum_j y_j \ln y_j \right) \quad (28)$$

Exergy destruction (Ex_D) taking place in any system component, during a process, can be calculated as [11]

$$Ex_D = \sum_k \left(1 - \frac{T_o}{T_k} \right) Q_k - W_{cv} + \sum_{in} Ex_{in} - \sum_{ex} Ex_{ex} \quad (29)$$

Exergy destruction of any component of the proposed system is calculated as a function of incoming fuel exergy. It is represented as follows

$$x_D = \frac{Ex_D}{Ex_{IN}} \quad (30)$$

Exergy loss is determined as a function of incoming fuel exergy. It is shown as follows

$$x_{Loss} = \frac{Ex_{Lost}}{Ex_{IN}} \quad (31)$$

5 Performance Parameters

The total power developed from the system is estimated as

$$W_{sys} = W_{SOFC} + W_{OVT} - W_{Aux} \quad (32)$$

where W_{Aux} denotes auxiliary power consumption and is estimated as follows

$$W_{Aux} = W_{C1} + W_{C2} + W_{OLP} \quad (33)$$

The net energetic efficiency of the designed power plant can be written as

$$\eta_{\text{sys}} = \frac{W_{\text{sys}}}{n_{\text{fuel}}LHV_{\text{fuel}}} \quad (34)$$

Exergetic efficiency of the proposed system is determined as

$$\phi_{\text{sys}} = 1 - \sum x_{\text{D}} - \sum x_{\text{Loss}} \quad (35)$$

6 Results and Discussions

Base case input parameters are shown in Table 1. System performance at base case is given in Table 2. In this section, the effect of major operating and designing plant parameters, viz. SOFC current density and cell temperature (T_{cell}) on major plant performance parameters has been examined.

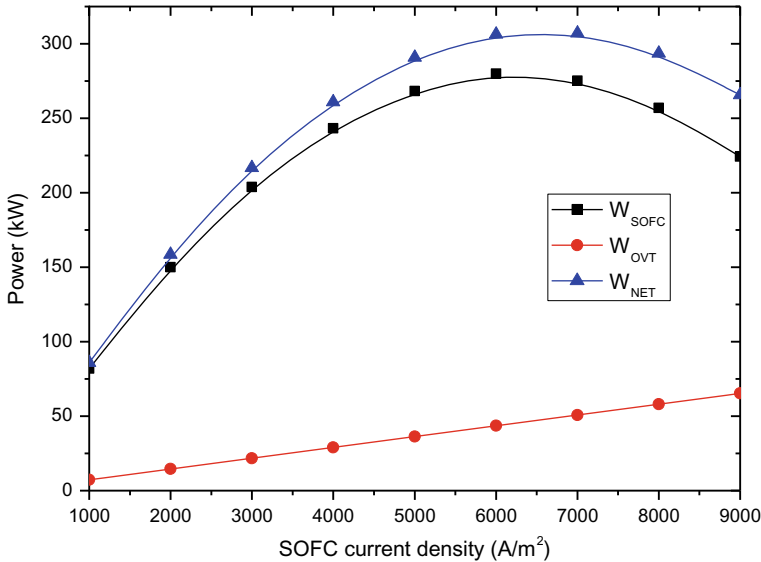
Figure 2 depicts the effect of SOFC current density from 1000 to 9000 A/m² on W_{SOFC} , W_{OVT} , and W_{NET} . It is seen from Fig. 3 that with the increase of current density, W_{SOFC} first increases, then reaches an optimal point, then decreases. Optimum power of SOFC found to be 280 kW at a current density of 6000 A/m². With the increase of current density, fuel consumption at the SOFC unit increases. Thus, W_{SOFC} increases with the increase of current density. It is also found that, W_{OVT} increases with the increase of current density. Increase of fuel and air

Table 1 Input parameter for base case performance analysis of the system

| Parameters | Values |
|--------------------------------|------------------------------------|
| SOFC operating temperature | 850 °C |
| SOFC current density | 2000 A/m ² |
| Cell area | 0.01 m ² |
| Number of cell | 500 |
| Number of stack | 20 |
| SOFC fuel utilization factor | 0.52 |
| SOFC oxygen utilization factor | 0.20 |
| Cathode pre-exponential factor | 1.3×10^9 A/m ² |
| Anode pre-exponential factor | 1.4×10^9 A/m ² |
| Activation energy for cathode | 120×10^3 kJ/kmol |
| Activation energy for anode | 110×10^3 kJ/kmol |
| Electrolyte thickness | 4×10^{-5} m |
| Anode thickness | 1×10^{-4} m |
| Cathode thickness | 0.0019 m |
| Interconnect thickness | 8.5×10^{-5} m |
| OVT inlet temperature | 280 °C |
| OVT inlet pressure | 30 bar |

Table 2 Base case performance parameters of the proposed system

| Parameters | Value |
|--|-----------|
| SOFC stack power (W_{stack}) | 7.5 kW |
| SOFC module power output (W_{SOFC}) | 150 kW |
| OVT power (W_{OVT}) | 14.51 |
| Auxiliary power demand (W_{Aux}) | 6.10 kW |
| Net power developed (W_{NET}) | 158.41 kW |
| Net energy efficiency (η_{sys}) | 61.87% |
| Net exergy efficiency (ϕ_{sys}) | 53.8% |

**Fig. 2** Effect of current density of power

consumption at 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, W_{OVT} also increases. It is observed that W_{NET} first increases, then reaches an optimal point, then decreases. Optimum W_{net} is found to be 307 kW at a current density of 6000 A/m².

Figure 3 illustrates the effect of SOFC current density in the operating range of 1000–9000 A/m² on energetic and exergetic efficiency of the power plant. It is observed that as the SOFC current density rises, energetic as well as exergetic efficiency decreases. As the current density increases, energetic efficiency as well as exergetic efficiency of the power plant decreases due to drop in cell voltage. Highest energetic and exergetic efficiencies of the power plant are estimated to be 67.05 and 58.17%, respectively.

Figure 4 depicts the effect of T_{cell} on W_{SOFC} , W_{OVT} , and W_{NET} . It is found that W_{SOFC} and W_{NET} reduce with the rise of T_{cell} . As the voltage decreases with the rise

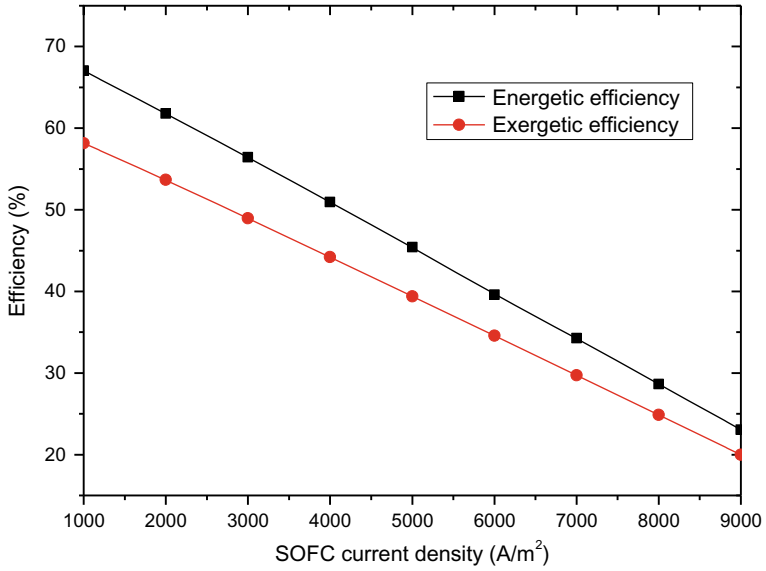


Fig. 3 Effect of current density of efficiency

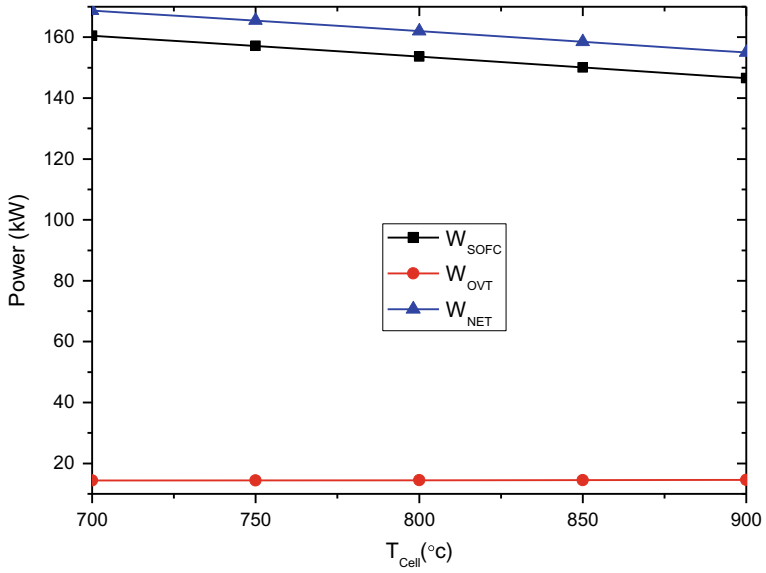


Fig. 4 Effect of cell temperature on power

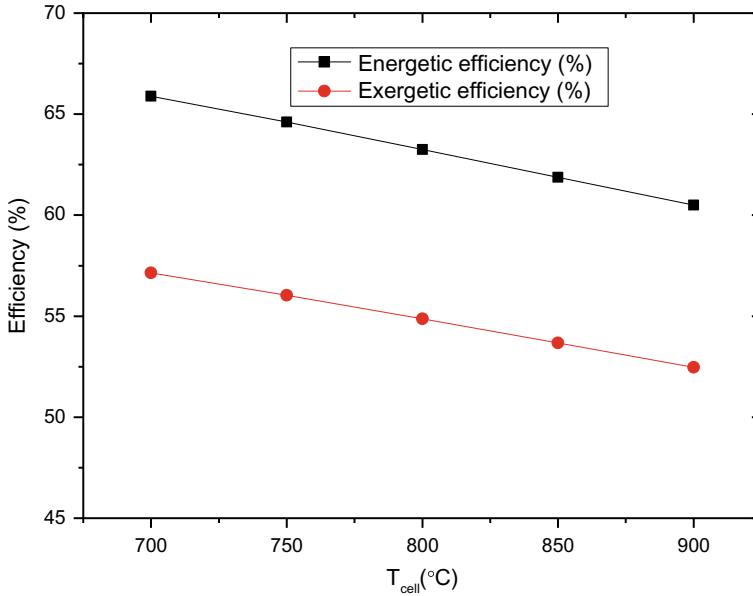
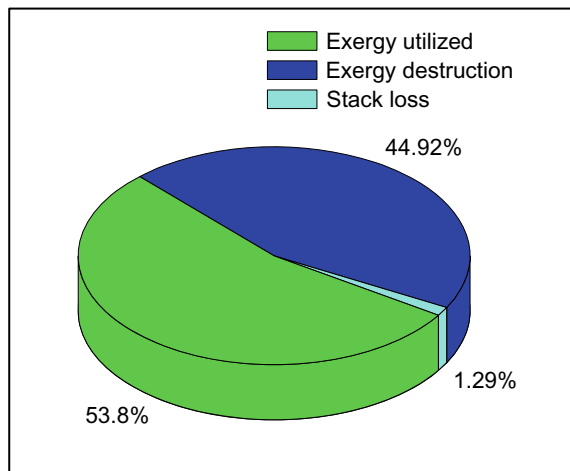


Fig. 5 Effect of cell temperature on efficiency

of T_{cell} , W_{SOFC} and W_{NET} also decreases. Maximum W_{NET} is obtained to be 168.76 kW at $T_{cell} = 700$ °C. Effect of T_{cell} does not have much effect of the performance of W_{OVT} .

Figure 5 illustrates the influence of T_{cell} on energetic and exergetic efficiency of the power plant. Performance of the system has been observed for the cell temperature in the range of 700–900 °C. It is found that as the T_{cell} increases, energetic

Fig. 6 Stack loss, useful exergy, and exergy destruction of system



as well as exergetic efficiency decreases. Drop of efficiency of the system is highly attributed to the decrease of W_{NET} . Thus, as the cell temperature increases, both energetic efficiency and exergetic efficiency of the system decreases.

Useful exergy, total exergy destruction, and stack loss of the integrated system with respect to total fuel exergy input have been depicted in the pie chart as shown in Fig. 6. The useful exergy, total exergetic destruction, and stack loss of the proposed power plant are found to be 53.8, 44.92, and 1.29%, respectively.

7 Conclusion

In this paper, a methane-fueled SOFC and ORC incorporated power plant is modeled and analyzed. Performances of the proposed system are found to be influenced by the major operating and design parameters, viz. current density of SOFC and cell temperature. The main conclusions are as follows:

- As the current density of SOFC increases, W_{NET} first increases, then reaches an optimal point, then decreases. Optimum W_{NET} is found to be 307 kW at a current density of 6000 A/m².
- Highest energetic and exergetic efficiency of the power plant are found to be 67.05 and 58.17%, respectively.
- Increase in cell temperature results in decrease of both energetic efficiency as well as exergetic efficiency of the system.
- The useful exergy, total exergetic destruction, and stack loss of the proposed power plant are found to be 53.8, 44.92, and 1.29%, respectively.

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