Reversible Solid Oxide Fuel Cell Connected to Solar PV/T System: Cell Electrochemical Modelling and Analysis

A K Mishra¹, D Roy¹ and S Ghosh¹
¹Department of Mechanical Engineering, Indian Institute of Engineering Science and Technology, Shibpur, Howrah 711103, West Bengal, India

Corresponding Author: aradhykumar@gmail.com

Abstract. In this paper, a novel power generation cum storage system employing reversible solid oxide fuel cell (RSOFC) has been proposed and modelled. The RSOFC is integrated with solar PV/T system. Here only the electrochemical modelling of the fuel cell unit has been presented and analysed thermodynamically. The RSOFC unit operates in steam electrolyser mode (during day time) as well as in fuel cell mode (during night time). The electrochemical model has been developed by using Engineering Equation Solver. Performance of RSOFC unit has been investigated under varying operating parameters viz. applied current density and operating cell temperature. For electrolyser mode of operation maximum efficiency is found to be 93% at a current density (J) 8000 A/m² and at cell temperature (T_{cell}) 1273K. Maximum efficiency during fuel cell mode of operation is found to be 77% at cell temperature 1073K and at current density 500 A/m².

1. Introduction

According to IEA report [1], fossil fuels contribute a major share of electricity production till now. Fossil based power plants are the major emitter of greenhouse gases. Therefore, designing advanced power generation system employing renewable energy sources is essential to neutralize greenhouse gas emissions. In that context, fuel cell technology has a potential to provide a clean and sustainable form of energy without emitting any polluting agents. Reversible solid oxide fuel cell (RSOFC) is a promising new technology which can operate in solid oxide fuel cell (SOFC) mode as well as in solid oxide steam electrolyser (SOSE) mode. RSOFC generally operates at a very high temperature (873-1273 K). Thus, it requires a high temperature heat source to preheat the incoming feed (H₂ and air in SOFC mode of operation, H₂O in SOSE mode of operation).

Akikur et al. [2] proposed a solar powered RSOFC based cogeneration system. The overall efficiency of the system is found to be 20% and 23% in the solar-SOSE mode and the solar-SOFC mode respectively. Wendel et al. [3] studied the performance of an intermediate temperature RSOFC and found that efficiency, more than 70% can be achieved at intermediate stack temperature (680°C). Kazempoor et al. [4] proposed a RSOFC based energy storage system in which they investigated the effect of operating parameters viz. temperature, gas composition and fuel utilization on cell voltage, at varying current densities. Visidumrongkul et al. [5] investigated the performance of SOSE integrated system for H₂ production. The effect of operating parameters viz. oxygen to carbon ratio, operating...
temperature and pressure have been reported. Ni et al. [6] conducted the parametric study of SOFC. They found that the activation and ohmic overpotentials decrease significantly with increasing cell temperature, whereas the concentration overpotential increases with rising cell temperature. Ghosh et al. [8] conducted a parametric study of SOSE and found that at increasing electrode porosity and pore size, the total voltage loss reduces. Stamatis et al. [9] studied a SOFC-GT system fed with ethanol and found that at higher current density, the SOFC-GT system is more efficient compared to SOFC unit. Roy et al. [10] performed energetic and exergetic analyses of a biomass based SOFC-GT-ORC system. Akkaya et al. [11] studied the performance of a combined system consisting of SOFC and ORC.

This paper proposes a novel power generation cum storage system employing a RSOFC and PV/T module. Electrochemical model of RSOFC system has been developed and analysed. Engineering Equation Solver (EES) was used to write codes for the model. Performance of RSOFC unit has been investigated under varying operating parameters viz. current density and cell temperature.

2. System description

The schematic of the proposed RSOFC integrated power generation cum storage system is depicted in Figure 1. RSOFC unit operates in SOSE mode (solid line in Figure 1) as well as in SOFC mode (dotted line in Figure 1). At this time, water is passed through solar thermal photovoltaic (PV/T) system where it takes heat from it. After that, it passes through parabolic trough solar collector (PTSC) where water is further heated and is converted into steam. Further superheating is done by Heat Exchanger 1 (HEx 1) where heat is extracted from outlet product of RSOFC. If further heating is required, then the steam is again passed through the Supplementary Heater 1 and then this superheated steam is supplied to cathode channel of RSOFC. Necessary electrical power required to run RSOFC, is consumed from PV/T unit. Water molecules will be dissociated into a mixture H₂+ H₂O and O₂. Oxygen gas, leaving from anode channel exit, is stored in oxygen storage tank after exchanging necessary heat in the HEx 1. The mixture of H₂+H₂O, after exchanging necessary heat in HEx 1, is fed to the separator, where H₂ is separated from the mixture. H₂O will be stored in the H₂O storage tank.

During night time in SOFC mode of operation (dotted line in Figure 1), stored hydrogen from hydrogen storage tank and air from the atmosphere will be fed in the RSOFC after necessary heating in heat exchanger 2 (HEx 2) and Supplementary Heater 2. Due to chemical reactions taking place in RSOFC unit, DC power is produced which further converted to AC power through the rectifier.

3. Mathematical model development

3.1 SOSE Mode of Operation

For a SOEC fed by electricity and water, the overall electrode reaction is:-

\[ \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2 \]  
(1)

The total electrical power demand \( P_{\text{SOSE}} \) is defined by:-

\[ P_{\text{SOSE}} = V_{\text{SOSE}} A_{\text{cell}} N \]  
(2)

where \( V_{\text{SOSE}} \) is the input potential of SOSE, \( J \) is current density, \( A_{\text{cell}} \) is area of cell and \( N \) is number of cells. The required voltage \( V_{\text{SOSE}} \) can be written as:-

\[ V_{\text{SOSE}} = E + \eta_{\text{ohmic}} + \eta_{\text{act,a}} + \eta_{\text{act,c}} + \eta_{\text{conc,a}} + \eta_{\text{conc,c}} \]  
(3)

where \( E \) is Equilibrium potential or Nernst potential, \( \eta_{\text{ohmic}} \) is ohmic overpotential, \( \eta_{\text{act,a}} \) is activation overpotential at anode, \( \eta_{\text{act,c}} \) is the activation overpotential at cathode, \( \eta_{\text{conc,a}} \) is concentration overpotential at anode and \( \eta_{\text{conc,c}} \) is concentration overpotential at cathode. Nernst potential or Equilibrium potential can be calculated as:-
\[ E = E^0 + \frac{RT}{2F} \ln \left( \frac{P_{H_2}^0}{P_{H_2O}^0} \right) \]  
\[ \sigma = 2F \left[ \eta_{\text{ohmic}} + \eta_{\text{act, a}} + \eta_{\text{act, c}} + \eta_{\text{conc, a}} + \eta_{\text{conc, c}} \right] \]

If \( \sigma \geq T \Delta S \) i.e. heat generation due to irreversibility is more than or equal to the heat required for water splitting reaction (T \Delta S) then no external heat is required but if \( \sigma < T \Delta S \) then heat production is less than the heat requirement hence external heat is required which is calculated by [8]:-
\[ Q_{\text{Heat,SOSE}} = \frac{J}{2F} (T \Delta S - \sigma) \]

### 3.2 SOFC Mode of Operation

For SOFC fed by H\(_2\) and air, the overall electrode reaction is:-
\[ H_2 + \frac{1}{2}O_2 \rightarrow H_2O \]

Power output \( (P_{\text{SOFC}}) \) in fuel cell mode can be expressed as:-
\[ P_{\text{SOFC}} = V_{\text{SOFC}} J_{\text{SOFC}} A_{\text{cell}} \]
where $J_{SOFC}$ is the produced current density in SOFC mode of operation which can be calculated as:

$$J_{SOFC} = 2\dot{N}_{H_2,\text{utilized}}F$$  \hspace{1cm} (10)

where $\dot{N}_{H_2,\text{utilized}}$ is molar flow rate of hydrogen consumed by RSOFC. The output voltage ($V_{SOFC}$) of a fuel cell is the difference of Nernst Potential ($E$) and total overpotential where total overpotential is the sum of ohmic overpotential, activation overpotential at anode and cathode and concentration overpotential at anode and cathode.

$$V_{SOFC} = E - \eta_{\text{ohmic}} - \eta_{\text{act},a} - \eta_{\text{act},c} - \eta_{\text{conca}} - \eta_{\text{concc}}$$  \hspace{1cm} (11)

where Nernst potential ($E$), the ohmic overpotential ($\eta_{\text{ohmic}}$), the activation overpotentials ($\eta_{\text{act}}$) can be calculated by the same equation those are used for electrolyser mode. The concentration overpotential can be calculated by [11]. Efficiency of SOFC ($\eta_{SOFC}$) is calculated by [2]:

$$\eta_{SOFC} = \frac{P_{SOFC}}{\dot{N}_{H_2,\text{inlet}}LHV_{H_2}}$$  \hspace{1cm} (12)

where $\dot{N}_{H_2,\text{inlet}}$ is the molar flow rate of hydrogen at inlet.

4. Model Validation

RSOFC model has been validated both in SOFC mode and SOSE mode of operation. The SOSE mode of operation is compared with the experimental work of Momma et al. [14], as shown in Figure 2. The SOFC model of operation is compared with the experimental work of Zhao et al. [15], as shown in Figure 3. The maximum error in between simulation and experimental work in SOSE mode is 4.5% and in SOFC mode is 7.7%.

5. Result and Discussion

In this paper, we have only analysed the RSOFC unit by varying different operating parameters such as current density and cell temperature. Input parameters needed for analysis is shown in Table 1. Figure 4 shows the effect of SOSE current density on hydrogen production rate at a temperature of 1073K.

| Parameter                  | Value |
|----------------------------|-------|
| Pressure (bar)             | 1     |
| Electrolyte thickness, L (μm) | 50    |
| Anode thickness, $d_a$ (μm) | 500   |
| Cathode thickness, $d_c$ (μm) | 50    |
| Number of cells, N         | 1000  |
| Area of each cell, $A_{cell}$ (m²) | 0.01  |
Since hydrogen production rate is directly proportional to SOSE cell current density, increased current density increases the hydrogen production rate, as shown in Figure 4. Efficiency is also found to increases continuously up to $J = 4000 \text{ A/m}^2$ and then remains almost unaffected by further increase in current density. Figure 5 depicts the influence of $T_{\text{cell}}$ and $J$ on the efficiency of RSOFC. It is observed that influence of $T_{\text{cell}}$ is not highly significant on efficiency at lower current densities. It is due to the fact that, at lower current densities, the requirement of heat energy is higher compared electrical energy. Efficiency of RSOFC unit is highly influenced by increasing operating current density and cell temperature. At elevated current density, electrical energy requirement is higher compared to thermal energy. Further at higher current density and elevated $T_{\text{cell}}$ amount of $H_2$ production increases. Hence high temperature and higher value of current density are desirable.

![Figure 4](image-url)
**Figure 4.** $J$ vs $H_2$ production and $J$ vs Efficiency at temperature of 1073 K.

![Figure 5](image-url)
**Figure 5.** Temperature vs Efficiency at different current density.

Figure 6 illustrates the effect of current density on power and efficiency of RSOFC working in fuel cell mode when cell temperature is held constant (1073K). It is observed that on increasing current density, power from RSOFC increases while its efficiency decreases. As current density increases, molar flowrate of $H_2$ consumption increases. Thus, power obtained from RSOFC increases at elevated current densities. Again, increase of current density results in lower operating voltage due to which efficiency decreases. Figure 7 shows the effect of temperature on power and efficiency of RSOFC working in fuel cell mode. From Figure 7 it is clear that as temperature increases both power and efficiency increases. It is due to the fact that at rising operating temperature, overpotentials decreases. Hence, cell voltage increases which further results in increase of power and efficiency.

![Figure 6](image-url)
**Figure 6.** Power and Efficiency vs $J$

![Figure 7](image-url)
**Figure 7.** Power and Efficiency vs $T$
6. Conclusion
In this study, a novel power generation cum storage system employing reversible solid oxide fuel cell (RSOFC) has been proposed and modelled. Electrochemical modelling of the fuel cell unit has been presented and analysed thermodynamically. Analysis predicted that performance of RSOFC unit is highly affected by operating parameters viz. current density and cell temperature. In SOSE mode of operation, under varying operating cell temperature from 973K to 1273K efficiency of the RSOFC unit is found to be in increasing nature at elevated current densities. Though, the performance of the RSOFC unit is not influenced at lower operating current densities. Maximum efficiency of RSOFC unit in SOSE mode found to be 93%, at $T_{\text{cell}}=1273K$ and $J=8000 \text{ A/m}^2$. In the SOFC mode of operation, efficiency of the RSOFC unit found to be decreasing at rising current densities. Maximum efficiency of the RSOFC unit in SOFC mode of operation found to be 77% at $T_{\text{cell}}=1073K$ and $J=500 \text{ A/m}^2$.

References
[1] https://www.iea.org/newsroom/news/2017/september/commentary-understanding-and-using-the-energy-balance.html
[2] Akikur R K, Saidur R, Ping H W and Ullah K R 2014 Performance analysis of a co-generation system using solar energy and SOFC technology Energy Convers. Manag.79 415–30
[3] Wendel C H, Kazempoor P and Braun R J 2015 Novel electrical energy storage system based on reversible solid oxide cells: System design and operating conditions J. Power Sources276 133–44
[4] Kazempoor P and Braun R J 2014 Model validation and performance analysis of regenerative solid oxide cells for energy storage applications: Reversible operation Int. J. Hydrogen Energy39 5955–71
[5] Visitdumrongkul N, Tippawan P, Authayanun S, Assabumrungrat S and Arpornwichanop A 2016 Enhanced performance of solid oxide electrolysis cells by integration with a partial oxidation reactor: Energy and exergy analyses Energy Convers. Manag.129 189–99
[6] Ni M, Leung M K H and Leung D Y C 2007 Parametric study of solid oxide fuel cell performance Energy Convers. Manag.48 1525–35
[7] AkGhosh S and De S 2006 Energy analysis of a cogeneration plant using coal gasification and solid oxide fuel cell Energy31 345–63
[8] Ni M, Leung M K H and Leung D Y C 2007 Parametric study of solid oxide steam electrolyzer for hydrogen production Int. J. Hydrogen Energy32 2305–13
[9] Stamatis A, Vinni C, Bakalis D, Tzorbatzoglou F and Tsiakaras P 2012 Exergy analysis of an intermediate temperature solid oxide fuel cell-gas turbine hybrid system fed with ethanol Energies5 4268–87
[10] 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. Policy19 1693–709
[11] Akkaya A V and Sahin B 2009 A study on performance of solid oxide fuel cell-organic Rankine cycle combined system 553–64
[12] Ferguson J R, Fiard J M and Herbin R 1996 Three-dimensional numerical simulation for various geometries of solid oxide fuel cells J. Power Sources58 109–22
[13] Ni M, Leung M K H and Leung D Y C 2007 Energy and exergy analysis of hydrogen production by solid oxide steam electrolyzer plant Int. J. Hydrogen Energy32 4648–60
[14] Momma A, Kato T, Kaga Y and Nagata S 1997 Polarization behavior of high temperature solid oxide electrolysis cells (SOEC) Nippon Seramikkusu Kyokai Gakujutsu Ronbunshi/Journal Ceram. Soc. Japan105 369–73
[15] Zhao F and Virkar A V. 2005 Dependence of polarization in anode-supported solid oxide fuel cells on various cell parameters J. Power Sources141 79–95