Proton conducting reversible SOFC integrated in a solar thermal power generation system

Angshuman Ghosh, Dibyendu Roy and Sudip Ghosh*

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

*Corresponding author; Email: sudipghosh.becollege@gmail.com

Abstract. This paper proposes a novel solar thermal power generation system that employs a proton conducting reversible solid oxide fuel cell (RSOFC-H) and a hybrid photovoltaic thermal module. The photovoltaic thermal module supplies electrical power to the solid oxide fuel cell (SOFC) while operating in electrolysis mode. The stored fuel (Hydrogen), generated by electrolysis mode is utilised to generate power in fuel cell mode. Electrochemical modelling and analysis of RSOFC-H is presented in this paper. The working condition of the system is: as a solid oxide steam electrolyser (SOSE) mode during the day time and solid oxide fuel cell (SOFC) mode during night time. Performance analysis of RSOFC-H has been conducted under varying operating and design parameters, such as current density and cell temperature. In SOSE mode of operation, efficiency has been observed to be almost constant with the variation of current density and it is obtained to be 78.31%. During SOFC mode of operation, maximum efficiency obtained is to be 64.62% at cell temperature of 873K and current density of 500A/m².

1. Introduction

Global energy demand has been increasing at a faster rate with the rapid infrastructural development, growth of population and economic expansion. During last 17 years, demand of energy has raised by 39% and, world economy by 85%. In 2017, energy demand has increased by 1.9%. Since 2010 this is the highest yearly increase [1]. Most of available power is produced from finite resources. These finite resources include coal, unprocessed oil, natural gas etc. Electricity generated from such resources leads to harmful emissions (CO₂, NOₓ, SOₓ etc.). Thus, at present, attention is given by energy researchers towards exploring and developing cleaner, energy efficient and sustainable mode of power generation. Renewable energy based power generation systems are able to fulfil all those requirements.

Power generation systems employing fuel cell technology is a promising way toward mitigating harmful emissions. Fuel cells are able to produce electricity without any harmful emissions when pure hydrogen is used as a fuel. Reversible solid oxide fuel cell (RSOFC) is one which can generate power during fuel cell mode of operation as well as produce pure hydrogen during electrolysis mode of operation. RSOFC with oxide ion conducting electrolyte (RSOFC-O) generally works at sufficiently high temperature (1073-1273K) [2]. This high operating temperature can be reduced significantly
when a proton conducting electrolyte is introduced in RSOFC (RSOFC-H). Proton conducting electrolyte also shows high ionic conductivity at low temperatures (873-1073K) [3]. Lyagaeva et al. [3] developed a proton conducting electrolyte material which is yittria and ytterbia co-doped BaCeO$_3$–BaZrO$_3$, incorporated in a SOFC. They found the ionic conductivity of the proton conducting electrolyte is quite high (2.4 mS/cm and 3.8mS/cm at 873K and 973K respectively). Kalinci and Dincer [4] investigated the performance of a proton conducting SOFC fed with hydrogen (H$_2$) and ammonia (NH$_3$). Maximum power density was found to be 3212A/m$^2$ at 1073K and 1 atm pressure when fed with H$_2$. A dysprosium doped BaCeO$_3$–BaZrO$_3$ proton conducting electrolyte for RSOFC built up by Lyagaeva et al. [5]. The ionic conductivity of this material was found to be 19 mS/cm and 13 mS/cm in wet air and wet H$_2$ atmosphere respectively at 873K. Patcharavorachot et al. [6] investigated the analysis of a proton conducting planar SOFC and the found that an anode supported SOFC-H had fetched best performance at a cell operating temperature of 1073K and 1 atmospheric pressure. Ni et al. [7] studied the electrochemical modelling of SOSE-H. They found that for proton conducting SOSE-H, cathode supported configuration is the most favourable configuration. Mishra et al. [8] analysed the performance of an oxide ion conducting RSOFC integrated with solar PV/T. The maximum energetic efficiency during SOSE and SOFC mode were noted to be 93% and 77% respectively. Roy et al. [9] investigated thermodynamically a biomass-based employing SOFC power generation system. They found system efficiency in the range of 30 to 55%. Akikur et al. [2] suggested an oxide ion conducting RSOFC based system integrated with solar power. During SOSE mode of operation, overall efficiency was found to be 20% and, during SOFC mode it is found to be 23%. Roy and Ghosh [10] performed energy and exergy analysis of a biomass based system employing SOFC. Maximum overall energetic efficiency of the system was noted to be 41.13%.

This paper proposes a novel solar thermal power generation system that employs a proton conducting RSOFC. Computational model has been developed and analyzed. Simulated results of RSOFC-H model have been validated with the reported experimental results. Cell performance is studied at different operational and design parameters.

2. System description

![Figure 1. Schematic of solar thermal power generation system](image)
RSOFC unit operates as SOSE mode during day time (shown by firm line) as well as SOFC mode during night time (shown by dotted line). During electrolysis mode of operation, this unit produces hydrogen gas. At day time water is supplied to solar photovoltaic thermal (PV/T) where temperature of water increases by consuming solar energy. Then it passed through a solar parabolic trough collector (PTSC). In this collector, temperature of water increases by absorbing incident solar radiation. If further heating is required, a supplementary heater is integrated with the system to raise the temperature of steam up to the operating cell temperature. This superheated steam is sent to the anode channel of RSOFC-H. Power required to operate the RSOFC-H is supplied by solar photovoltaic thermal unit (shown by red colour firm line). Water molecule will be converted into H₂ and a mixture of O₂ and H₂O. Finally, H₂ gas is stored in a storage tank.

At night time, RSOFC-H operates in SOFC mode. Hydrogen (H₂) is supplied from hydrogen storage tank to the anode channel and air is supplied to the cathode channel. At RSOFC-H chemical energy of fuel is converted into electrical energy. Unutilised fuel is supplied to the afterburner for further combustion. Heat energy obtained from this combustion product can be utilised to heat-up incoming hydrogen and air.

3. Mathematical model establishment
The basic electrochemical model of the reversible solid oxide fuel cell (RSOFC) unit has been developed for the study.

3.1 SOSE mode of operation
The overall reaction during SOSE mode of operation is [7]

\[ H_2 + 0.5O_2 \Rightarrow H_2O \]  (1)

Total power required for hydrogen (H₂) generation is calculated by [8]

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

where \( V_{SOSE} \) represents supply voltage of SOSE, \( J_{SOSE} \) denotes the current density, \( A_{Cell} \) represents the area of each cell and \( N \) represents total number of cell.

Input cell voltage can be calculated by [12]

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

where \( E \) defines Nernst potential, \( \eta_{ohmic}^{SOSE} \) defines ohmic over-potential, \( \eta_{act,a}^{SOSE} \) and \( \eta_{act,c}^{SOSE} \) define activation over-potential at anode and cathode respectively, \( \eta_{conc,a}^{SOSE} \) and \( \eta_{conc,c}^{SOSE} \) define concentration over-potential at anode and cathode respectively.

Nernst potential can be calculated as [4]

\[ E = E^0(T,P_0) - \frac{RT}{2F} \ln \left( \frac{P_{H_2}P_{O_2}}{P_{H_2O}} \right) \]  (4)

where \( R \) is ideal gas constant, \( T \) is cell operating temperature, \( P \) is the atmospheric pressure, \( F \) is Faraday’s constant, \( P_{H_2O}, P_{H_2} \) and \( P_{O_2} \) is partial pressure of H₂O, H₂ and O₂ at electrode respectively and \( E^0(T,P_0) \) is the standard potential.

\[ E^0(T,P_0) = 1.253 - 2.4516 \times 10^{-4}T \]  (5)

Ohmic over-potential and activation over-potential can be obtained from Patcharavorachot et al. [5]. Concentration over-potential can be evaluated by Ni et al. [7]. Efficiency of SOSE-H can be calculated by [12]
\[ \eta_{SOSE}^{En} = \frac{LCV_{H_2} \times \dot{N}_{H_2,\text{out}}}{P_{SOSE} + Q_{\text{heat,SOSE}} + Q_{\text{heat,H}_2O}} \]  

where \( LCV_{H_2} \) is lower calorific value of hydrogen, \( Q_{\text{heat,SOSE}} \) represents the thermal energy input for SOSE, \( Q_{\text{heat,H}_2O} \) represents the heat required to increase the temperature of \( H_2O \) and \( \dot{N}_{H_2,\text{out}} \) is the molar flow rate of \( H_2 \).

Heat given to SOSE cell is evaluated by [12]

\[ \left[ T\Delta S - S_{\text{gen}} \right] \]

Over-potentials in SOSE mode of operation will result in heat production due to entropy generation \( (S_{\text{gen}}) \) [12]

\[ S_{\text{gen}} = 2F(\eta_{\text{ohmic}}^{SOSE} + \eta_{\text{act,a}}^{SOSE} + \eta_{\text{act,c}}^{SOSE} + \eta_{\text{conc,a}}^{SOSE} + \eta_{\text{conc,c}}^{SOSE}) \]  

If \( S_{\text{gen}} \geq T\Delta S \), production of heat due to irreversibility is equal to or more than the required heat for electrolysis and no external heat is required for the SOSE cell. If \( S_{\text{gen}} \leq T\Delta S \), heat generation is lower than the heat requirement thus external heat is required.

### 3.2 SOFC mode of operation

During SOFC mode if pure \( H_2 \) is fed at the electrode (anode), the overall reaction is [14]

\[ H_2 + 0.5O_2 \Rightarrow H_2O \]  

Power output is a fuel cell can be calculated as [8]

\[ P_{SOFC} = V_{SOFC}J_{SOFC}N_{\text{cell}}A_{cell} \]  

where \( J_{SOFC} \) is the produced current density.

Current density can be calculated as [8]

\[ J_{SOFC} = 2 \dot{N}_{H_2,\text{consumed}} F \]  

where \( \dot{N}_{H_2,\text{consumed}} \) is the molar flow rate of \( H_2 \) utilised by SOFC-H.

The output cell voltage of SOFC-H can be calculated by Substitute the total over-potentials (sum of ohmic, activation and concentration over-potentials) from Nernst potential and can be expressed as [4]

\[ V_{SOFC} = E - \left( \eta_{\text{ohmic}}^{SOFC} + \eta_{\text{act,a}}^{SOFC} + \eta_{\text{act,c}}^{SOFC} + \eta_{\text{conc,a}}^{SOFC} + \eta_{\text{conc,c}}^{SOFC} \right) \]  

Nernst potential (E), ohmic over-potential \( (\eta_{\text{ohmic}}^{SOFC}) \) and activation \( (\eta_{\text{act}}^{SOFC}) \) over-potential can be find out by the same equations as used in SOSE mode of operation.

The concentration over-potential can be obtained by Dincer et al. [4]. Efficiency of SOFC-H is evaluated by [2]

\[ \eta_{SOFC} = \frac{P_{SOFC}}{\dot{N}_{H_2,\text{inlet}} \times LCV_{H_2}} \]  

where \( \dot{N}_{H_2,\text{inlet}} \) denotes the molar flow rate of \( H_2 \) at inlet and \( LCV_{H_2} \) is the lower calorific value of \( H_2 \).
4. Results and discussion
In this study, only the performance analysis of RSOFC-H has been investigated by modifying the operating conditions such as current density and operating temperature. Input parameters used for this study is given in Table 1.

| Parameters                        | Values       |
|-----------------------------------|--------------|
| Pressure (P)                      | 1 bar        |
| Area of cell (A<sub>cell</sub>)   | 0.01m<sup>2</sup> |
| Cell temperature (T)              | 873K         |
| Electrolyte thickness (τ<sub>elec</sub>) | 25μm       |
| Anode thickness (τ<sub>a</sub>)    | 500μm        |
| Cathode thickness (τ<sub>c</sub>)  | 50μm         |
| Electrode porosity (ε)            | 0.4          |
| Ionic conductivity (λ, at 873K)   | 0.24S/m      |
| Average electrode pour radius (r) | 0.5μm        |

Table 1. Input parameters [3, 4]

Figure 2 shows the influence of current density on hydrogen (H<sub>2</sub>) gas production rate and cell efficiency at cell temperature 873K. Hydrogen production rate is a function of current density. It is seen from figure 2 that hydrogen production rate has been increased proportionally with the rise in current density. It is due to the fact that with the increase in current density rate of cell reaction increases, which in turn increases hydrogen production rate. It is also seen from figure 2 that efficiency of SOSE-H remains constant with the rise in current density.

Current density influences the power output and cell efficiency of SOFC-H, as shown in figure 3. It is observed from figure 3 that with the rise in current density, power output rises initially then reaches a maximum and finally decreases. It is because of the fact that at higher current density total over-potential rises which in turn reduces the cell voltage and power output. The maximum value of power density reaches 14.62 KW at current density of 3300 A/m<sup>2</sup>. It is also seen from figure 3 that the efficiency of SOFC-H decreases with the rise in current density. As the current density increases irreversible voltage losses increase. Thus, efficiency of the cell decreases.

Figure 4 depicts that influence of current density (J) and cell temperature (T<sub>cell</sub>) on the cell voltage in SOSE-H. As the cell temperature increases, cell voltage of SOSE-H decreases. High operating temperature provides better ionic conductivity of electrolyte. Thus, total over potential reduces which results in decrease in cell voltage. Again, cell voltage of SOSE-H also depends on current density. From figure 4, it is observed that with the increase in current density there is an increase of cell
voltage. The trends are so observed because of the fact that with the increasing current density, total over-potential increases.

Power output of SOFC-H depends on cell temperature and current density. Figure 5 shows the influence of cell operating temperature \( T_{\text{cell}} \) and current density \( J \) on power output in SOFC-H. It is observed that power output increases with the rise in cell operating temperature as well as increase in current density. As the temperature increases, ionic conductivity of the electrolyte also increases which results in reduction of irreversible voltage losses. Thus, power output increases with increasing cell operating temperature.

From the above discussion, it can be stated that the performance of RSOFC-H is highly influenced by cell operating temperature and current density. The values of some output parameters such as cell voltage, power density, efficiency (during SOFC mode) and hydrogen production rate (during SOSE mode) at the base case (873K and 3000A/m\(^2\)) are given in Table 3.

| SOFC-H mode | SOSE-H mode |
|-------------|-------------|
| Cell voltage | 0.488V      | \( \text{H}_2 \) production rate | 1.12 kg/hr |
| Power output | 14.48KW     | Cell Efficiency | 78.49% |
| Cell efficiency | 32.74% |

Table 3. RSOFC-H model performance parameters (at 873K and 3000A/m\(^2\))
5. Conclusions

This study has presented a novel solar thermal power generation system integrated with proton conducting reversible solid oxide fuel cell. An electrochemical modelling of RSOFC-H has been done. Simulated results of RSOFC-H model have been validated with the reported experimental results. It is seen that performance of RSOFC-H is highly influenced by cell operating temperature and current density. During electrolysis mode of operation the efficiency has been found to be almost constant where as hydrogen production rate has been increased with the rise in current density. During fuel cell mode of operation, a decrement in efficiency of SOFC-H is observed with the rise in current density and maximum efficiency has been noted to be 64.62% at cell temperature of 873K and current density of 500A/m².

References

[1] IEA 2017 Market Report Series energy efficiency 2017 IEA Publ. 1–143
[2] Akikur R K, Saidur R, Ping H W and Ullah K R 2014 Performance analysis of a cogeneration system using solar energy and SOFC technology Energy Convers. Manag. 79 415–30
[3] Lyagaeva J, Vdovin G, Hakimova L, Medvedev D, Demin A and Tsiakaras P 2017 BaCe₀.₅Zr₀.₃Y₀.₂YbₓO₃₋ₓproton-conducting electrolytes for intermediate-temperature solid oxide fuel cells Electrochim. Acta 251 554–61
[4] Kalinci Y and Dincer I 2017 Analysis and performance assessment of NH₃ and H₂ fed SOFC with proton-conducting electrolyte Int J Hydrogen Energy 43 1–13
[5] Lyagaeva J, Danilov N, Vdovin G, Bu J, Medvedev D, Demin A and Tsiakaras P 2016 A new Dy-doped BaCeO₃-BaZrO₃proton-conducting material as a promising electrolyte for reversible solid oxide fuel cells J. Mater. Chem. A 4 15390–9
[6] Patcharavorachot Y, Brandon N P, Paengjuntuek W, Assabumrungrat S and Arpornwichanop A 2010 Analysis of planar solid oxide fuel cells based on proton-conducting electrolyte Solid State Ionics 181 1568–76
[7] Ni M, Leung D Y C and Leung M K H 2008 Electrochemical modeling of ammonia-fed solid oxide fuel cells based on proton conducting electrolyte J. Power Sources 183 687–92
[8] Mishra A K, Roy D and Ghosh S 2018 Reversible Solid Oxide Fuel Cell Connected to Solar PV/T System: Cell Electrochemical Modelling and Analysis IOP Conference Series: Materials Science and Engineering 377 0–6
[9] Roy D, Samanta S and Ghosh S 2018 Thermodynamic analysis of a biomass based solid oxide fuel cell integrated advanced power generation system IOP Conference Series: Materials Science and Engineering 377 0–7
[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 Technologies and Environmental Policy 19 1693–709
[11] Ni M, Leung M K H and Leung D Y C 2008 Theoretical analysis of reversible solid oxide fuel cell based on proton-conducting electrolyte J. Power Sources 177 369–75
[12] Koumi Ngoh S, Ayina Ohandja L M, Kemajou A and Monkam L 2014 Design and simulation of hybrid solar high-temperature hydrogen production system using both solar photovoltaic and thermal energy Sustainable Energy Technologies and Assessments 7 279–93
[13] Ni M, Leung M K H and Leung D Y C 2007 Parametric study of solid oxide fuel cell performance Energy Conversion and Management 48 1525–35
[14] Ni M, Leung M K H and Leung D Y C 2007 Mathematical modelling of proton-conducting solid oxide fuel cells and comparison with oxygen-ion-conducting counterpart Fuel Cells 7 269–78