

## **Thermodynamic Analysis of a Solid Oxide Fuel Cell with internal Reforming**

**Tushar Choudhary<sup>1</sup>, Dr. Sanjay<sup>2</sup>**

**National Institute of Technology, Jamshedpur**

### **Abstract:-**

Solid oxide fuel cell (SOFC) systems hold great promise as a sustainable power source because of their high efficiency, fuel flexibility and ability to be combined with other systems to make hybrids with even higher efficiency. However, SOFC can be operated with various fuels because of the high operation temperature and with the catalyst used some fuels can be even internally reformed. This Paper concentrates on Thermodynamic analysis of Solid Oxide fuel cell (SOFC); in SOFC direct conversion from chemical energy to electrical energy takes place at high temperature, in form of by product steam is generated which can be utilized in co generation purpose. In thermodynamic model of SOFC planer cell configuration is adopted and which is powered by syn gas. In fuel cell operation parameters like fuel utilization ratio and air recirculation ratio are altered in order to evaluate thermodynamic performance. For different values of current densities the output parameters like voltage, cell-efficiency and power output are examined. It has been observed on increasing fuel utilization factor and decreasing the air recirculation ratio significantly affects the cell performance.

### **Introduction**

In recent year the consumption of fossil fuel has been significantly increased. The power sector is growing and is the largest and fastest-growing area of energy demand and has risen from 22% to 36% of total energy consumption between 1990 and 2011, according to the IEA. Also as per IEA the fossil fuel provides 73% of the total energy needs of power generation sector [1]. Due to this excessive dependence on fossil fuel for power generation (across the globe) CO<sup>2</sup> concentration in the atmosphere has been continuously increasing from 315ppmv (1958) to 385ppmv (2008) [2]. Fuel-cell being a relatively zero GHG emission energy conversion cycle has been chosen for analysis.

Solid Oxide fuel cell (SOFC) is a solid state electrochemical device in which direct energy transformation takes place in form of chemical to electrical at high temperature of about 700-1200 °C. At high temperature oxidation of fuel takes place at porous anode and cathode which is layered with an electrolyte. The main aspect of SOFC is nearly zero emission, stability, sizing flexibility, efficiency and a perfect candidate for utilization of waste heat. In this paper direct internal reforming has been adopted for analysis due to

advantages related to lesser emission as compared to other reforming technique. SOFC are capable of handling a wide range of gaseous fuels with major constituent  $H_2$  and  $CO$ . Fuel such as methane, methanol, ethanol, biogas,  $H_2S$ , etc are some of the possible fuels. Research investigating the feasibility of these fuels for SOFC has been reported in the literature [6-8].

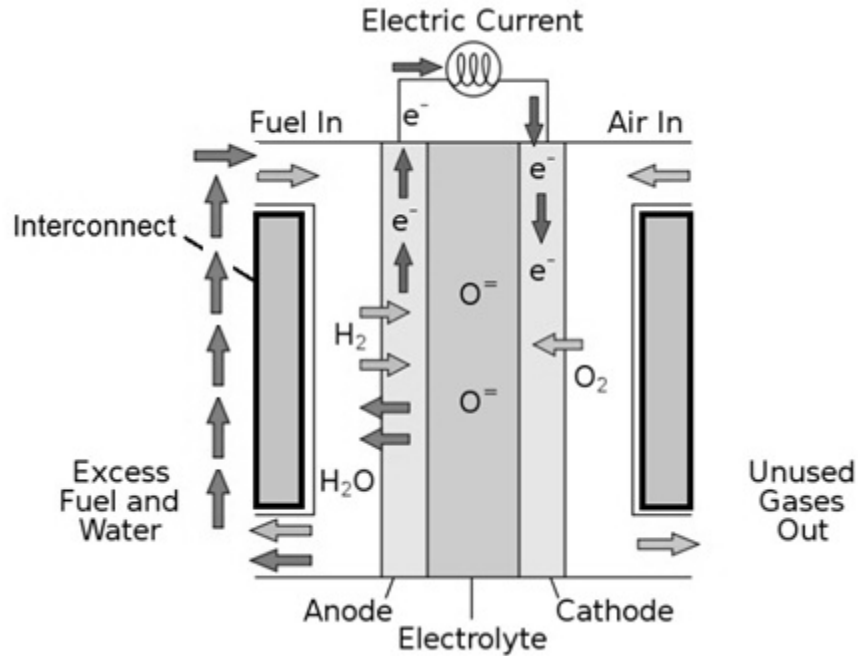


Figure 1 depicts the schematic diagram of solid oxide fuel cell. The fuel cell has been modeled to work on syn gas at elevated temperature of around 1350K.

In 1888 W. H Nernst proposed the basic idea and the material for electrochemical cell and on the basis of his named his equation has been termed as Nernst equation which further modified by Baur, Preis, Davtyan, Karoliussen, Achenbach and others at the beginning of 19th century. In 1930 Baur and Preis conducted experiments on solid oxide fuel cell with various electrolytes. Further in 1940 Davtyan conducted similar experiments with some additives added to electrolyte in order to enhance the performance. By the end of 1950 research in the field of SOFC accelerated and was taken up by primer organization the Central Technical Institute in The Hague, Netherlands, Consolidation Coal Company, Pennsylvania, and General Electric, Schenectady, New York. Later with the advancement in fuel cell technology the various challenges related to SOFC where addressed. NACA funded significant research in this area to power there various space craft's once they entered deep space. NACA later on proposed the integration of SOFC module with Gas turbine engines to deliver high performance of energy conversion [3].

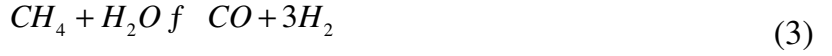
## Thermodynamic Model

A single cell considered during investigation has been shown in fig 1. Fuel mixture (Syn gas) enters the fuel channel and the outlet gases from anode have been recirculated such that fuel and recirculated gases continue to enter the anode. At anode steam reforming of methane, water gas shift and electrochemical reaction occurs simultaneously. The cell operating boundary conditions are tabulated in Table 1

**Table 1 Cell Operating Condition**

Input Parameter	Value
Operating temperature (T)	1350K
Temperature difference between inlet and exit ( $\Delta T$ )	473K
Pressure of the cell (P)	1bar
Active surface area (A)	500cm <sup>2</sup>
Exchange current density of anode ( $i_{cd,a}$ )	0.65A/cm <sup>2</sup>
Exchange current density of cathode ( $i_{cd,c}$ )	0.25A/cm <sup>2</sup>
Effective gaseous diffusivity through the anode ( $D_{a,eff}$ )	0.2cm <sup>2</sup> /s
Effective gaseous diffusivity through the cathode ( $D_{c,eff}$ )	0.05 cm <sup>2</sup> /s
Thickness of anode ( $\tau_a$ )	50 $\mu$ m
Thickness of electrolyte ( $\tau_e$ )	10 $\mu$ m
Thickness of cathode ( $\tau_c$ )	50 $\mu$ m

The gases exiting the fuel channel includes high level of water vapour, and is hence recirculated. Cathode reaction is where oxidation takes place due stripping of electrons from O<sub>2</sub> where after O<sup>2-</sup> ions diffuses through cathode electrolyte interface and migrates across the electrolyte to reacts with H<sub>2</sub><sup>+</sup> which has diffused from the anode to the anode electrolyte interface to produce current. The Electrochemical reactions take place within the fuel cell:



Overall Fuel Cell Reaction:



$$E_{Nernst} = -\frac{\Delta \bar{G}_T^0}{n_e F} + \frac{RT}{n_e F} \ln \left( \frac{X_{H_2} X_{O_2}^{0.5}}{X_{H_2O}} \right) + \frac{1}{2} \frac{RT}{n_e F} \ln \left( \frac{P}{P^o} \right) \quad (6)$$

$$E_{act} = E_{act,a} + E_{act,c} = \frac{RT}{F} \cdot \sinh^{-1} \left( \frac{i}{2i_{cd,a}} \right) + \frac{RT}{F} \cdot \sinh^{-1} \left( \frac{i}{2i_{cd,c}} \right) \quad (7)$$

$$E_{ohm} = R_{ohm} \cdot i = \left( \frac{\tau_a}{\sigma_a} + \frac{\tau_{elec}}{\sigma_{elec}} + \frac{\tau_c}{\sigma_c} \right) \cdot i = \left( R_{contact} + \sum_k^n \rho_k \cdot L_k \right) \cdot i \quad (8)$$

$$E_{conc} = E_{conc}^a + E_{conc}^c = \left[ \frac{-RT}{n_e F} \ln \left( 1 - \frac{i}{i_{as}} \right) + \frac{RT}{n_e F} \ln \left( 1 + \frac{X_{H_2} \cdot i}{X_{H_2O} \cdot i_{as}} \cdot \frac{P}{P^o} \right) \right] + \left[ \frac{-RT}{n_e F} \ln \left( 1 - \frac{i}{i_{cs}} \right) \right] \quad (9)$$

$$E = E_N - E_{act} - E_{ohm} - E_{conc} \quad (10)$$

$$W_{fc} = I \cdot E, \quad \eta_{cell} = \frac{W_{fc}}{n_e \cdot LHV} \quad (11)$$

In cell, the actual voltage reduces due to presence of irreversibility. This irreversibility is due to various losses also termed as “polarization”. Here three types of polarizations occur i.e. Ohmic, Activation and concentration which are specified as under. Are considered and calculated through equation (7)-(9).

In high temperature fuel cell the activation loss is quite less whereas in low and medium temperature fuel cell is more significant causing higher level of voltage drop from ideal voltage because at electrode –electrolyte interface there is sluggishness of reaction taking

placeAt cathode, the quantum of activation loss is higher than anode due to lower exchange current density. The activation loss can be determined from Butler-Volmer equation (7):

The ohmic loss due to electrical resistance to the flow of electron/ion through circuit/electrolyte. In order to overcome this loss high conductivity electrodes material should be so chosen to have higher electrical conductivity. If the reactant gases contain impurities this loss gets significantly increased. It has been determined as under (8) by using equation 10 the cell potential can be determined in which all losses are deducted from Nernst potential. Furthermore, the cell power output and efficiency of SOFC are given by expression 11

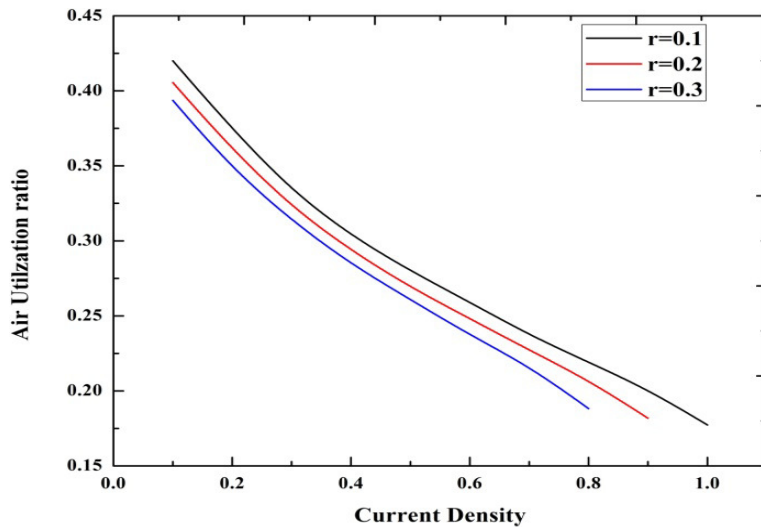


Figure 2 Effect of fuel recirculation ratio on air utilization ratio

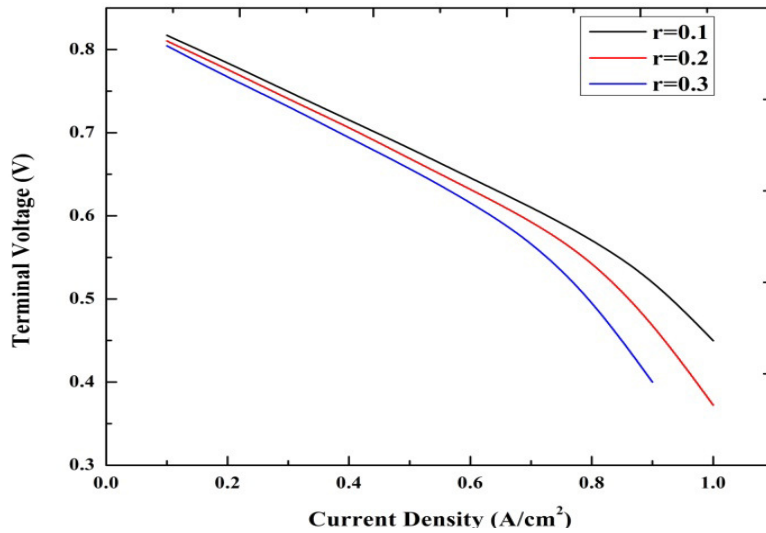


Figure 3 Effect of recirculation ratio on Terminal Voltage

In figure 2 and 3 shows the effect of recirculation ratio on air utilization ratio and cell terminal voltage. It has been seen that the abrupt change is there in air utilization as recirculation ratio increases. Similarly for cell terminal voltage decreases as recirculation ratio increases. It has also found the 6% variation is there in recirculation ratio of 0.1 in comparison with 0.3.

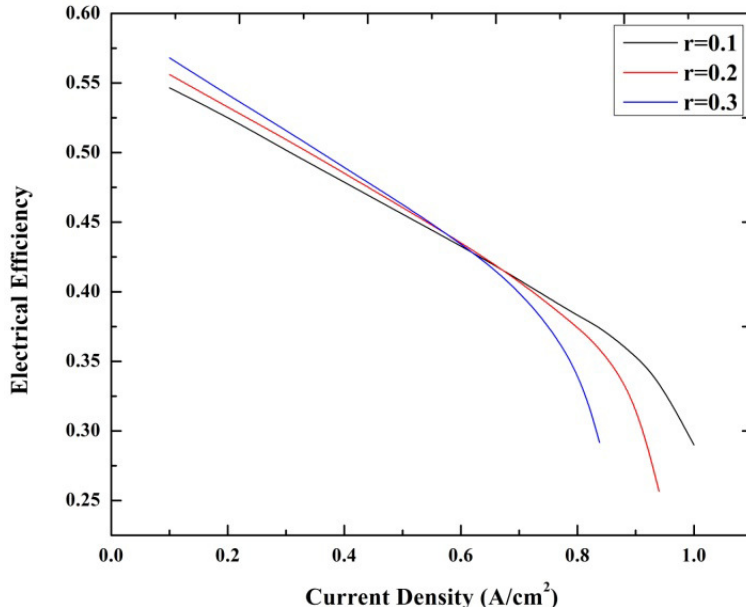


Figure 4 Effect of recirculation ratio on cell Electrical Efficiency

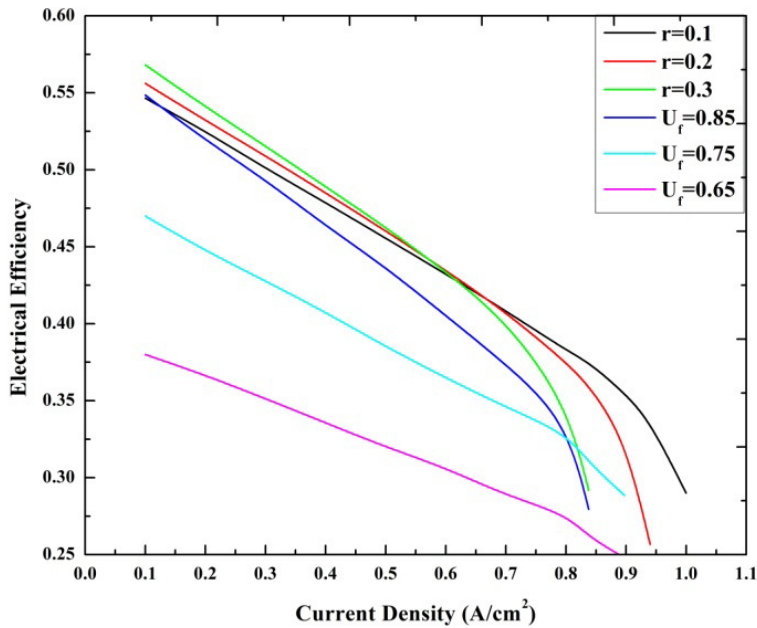


Figure 5 Effect of fuel utilization and recirculation ratio on Electrical Efficiency

In figure 4 and 5 shows the effect of fuel utilization and recirculation ratio on Electrical Efficiency. It has observed that on increasing current density the electrical efficiency decreases linearly as same for recirculation ratio and fuel utilization factor. But it is interesting to know that fuel utilization factor converges earlier as on comparison with recirculation ratio at higher current density.

## Conclusion

It has been seen that on increasing recirculation ratio and fuel utilization factor, air utilization ratio significantly decreases as the variation of air utilization also declines along with the increase in current density but the trend is more extendable for fuel utilization ratio. At terminal voltage of lower recirculation ratio has significant as compared to other whereas for higher fuel utilization ratio the terminal voltage is confined within the less range of current density. Similarly for electrical efficiency the same trend has been seen as for the terminal voltage. On the bases of these parameters the thermodynamically and economically effective conditions are examined and discussed. Furthermore the obtained results facilitates in optimization of the DIR-SOFC.

## Scope of Future work

- CFD analysis can be performed to analysis thermo-hydrodynamic characteristic.
- Implementing Artificial Roughness in SOFC.
- Changing flow configuration thermal performance can be optimized.
- Various SOFC based Application can be explored.

## Nomenclature

$A$	Active surface area, $\text{cm}^2$
$D_{a\text{eff}}$	Effective gaseous diffusivity through the anode, $\text{cm}^2/\text{s}$
$D_{c\text{eff}}$	Effective gaseous diffusivity through the cathode, $\text{cm}^2/\text{s}$
$E$	Voltage, V
$F$	Faraday constant, C
$-h$	Specific molar enthalpy, J/mol
$H$	Enthalpy flow rate, W
$i_{cd,a}$	Exchange current density of anode, $\text{A}/\text{cm}^2$
$i$	Current density, $\text{A}/\text{cm}^2$
$i_{cd,c}$	Exchange current density of cathode, $\text{A}/\text{cm}^2$
$i_{as}$	Anode-limiting current density, $\text{A}/\text{cm}^2$

$i_{cs}$	Cathode-limiting current density, A/cm <sup>2</sup>
$I$	Current, A
$K$	Equilibrium constant
$T$	Thickness of a cell component, $\mu\text{m}$
$LHV$	Lower heating value, J/mol
$M$	Molecular weight, g/mol
$n_e$	Number of Electrons
$R$	Recirculation ratio
$P$	Pressure, bar
$R$	Universal gas constant, J/molK
$T$	Temperature, K
$U_F$	Fuel Utilization ratio
$U_a$	Air Utilization ratio
$W_{fc}$	Power output of cell, W
$X$	Molar Concentration

### ***Greek Letter***

$P$	Electrical resistivity of the cell components
$H$	Cell Efficiency
$\Delta\bar{G}$	Change in specific molar gibbs free energy j/mol

### ***Subscripts***

$A$	Anode
$cat$	Cathode
$conc$	Concentration
$elec$	Electrolyte
$F$	Fuel
$ohm$	Ohmic

### ***Superscripts***

$O$	Standard State
-----	----------------

## References

[1] U.S. Energy Information Administration, International Energy Agency, BP Statistical Review. <http://www.eia.gov/countries/cab.cfm?fips=in>

[2] Earth system research laboratory Global monitoring Division, 2008, NOAA/ESRI, Boulder, CO.



- [3] Marvin Warshay and Paul R. Prokopius, *The Fuel Cell in Space: Yesterday, Today and Tomorrow*, NASA Technical Memorandum 102366, Lewis Research Center Cleveland, Ohio
- [4] Costamagna P, Selimovic A, Del Borghi M, Agnew G. Electrochemical model of the integrated planar solid oxide fuel cell (IP-SOFC). *Chem Eng J* 2004; 102:61–9.
- [5] Lucchese P, Varoquaux A. High temperature SOFC cells: state of the art and prospects. *CLEFS CEA* 2001; N° 44(Winter 2000–2001):57–9.
- [6] Yaofan Yi, Ashok D. Rao, Jacob Brouwer, G. Scott Samuelsen, Fuel flexibility study of an integrated 25 kW SOFC reformer system, *Journal of Power Sources*, Volume 144, Issue 1, 1 June 2005, Pages 67–76
- [7] K Eguchi, H Kojo, T Takeguchi, R Kikuchi, K Sasaki, Fuel flexibility in power generation by solid oxide fuel cells, *Solid State Ionics*, Volumes 152–153, December 2002, Pages 411–416
- [8] Eric D. Wachsman, Kang Taek Lee, Lowering the Temperature of Solid Oxide Fuel Cells, *Science* 18 November 2011: Vol. 334 no. 6058 pp. 935-939
- [9] Achenbach E, Riensche E. Methane/steam reforming kinetics for solid oxide fuel cells. *J. Power Sources* 1994; 52:283–8.
- [10] Khaleel MA, Selman JR. In: Singhal SC, Kendall K, editors. *High-temperature solid oxide fuel cells-fundamentals, design and applications*. Oxford: Elsevier Science; 2003. p. 293–331.