Chief Editor

Dr. A. Singaraj, M.A., M.Phil., Ph.D.

Editor

Mrs.M.Josephin Immaculate Ruba

EDITORIAL ADVISORS

1. Prof. Dr.Said I.Shalaby, MD,Ph.D.
   Professor & Vice President
   Tropical Medicine,
   Hepatology & Gastroenterology, NRC,
   Academy of Scientific Research and Technology,
   Cairo, Egypt.
2. Dr. Mussie T. Tessema,
   Associate Professor,
   Department of Business Administration,
   Winona State University, MN,
   United States of America,
3. Dr. Mengsteab Tesfayohannes,
   Associate Professor,
   Department of Management,
   Sigmund Weis School of Business,
   Susquehanna University,
   Selinsgrove, PENN,
   United States of America,
4. Dr. Ahmed Sebihi
   Associate Professor
   Islamic Culture and Social Sciences (ICSS),
   Department of General Education (DGE),
   Gulf Medical University (GMU),
   UAE.
5. Dr. Anne Maduka,
   Assistant Professor,
   Department of Economics,
   Anambra State University,
   Igbariam Campus,
   Nigeria.
6. Dr. D.K. Awasthi, M.SC., Ph.D.
   Associate Professor
   Department of Chemistry,
   Sri J.N.P.G. College,
   Charbagh, Lucknow,
   Uttar Pradesh. India
7. Dr. Tirtharaj Bhoi, M.A, Ph.D,
   Assistant Professor,
   School of Social Science,
   University of Jammu,
   Jammu, Jammu & Kashmir, India.
8. Dr. Pradeep Kumar Choudhury,
   Assistant Professor,
   Institute for Studies in Industrial Development,
   An ICSSR Research Institute,
   New Delhi- 110070, India.
9. Dr. Gyanendra Awasthi, M.Sc., Ph.D., NET
   Associate Professor & HOD
   Department of Biochemistry,
   Dolphin (PG) Institute of Biomedical & Natural Sciences,
   Dehradun, Uttarakhand, India.
10. Dr. C. Satapathy,
    Director,
    Amity Humanity Foundation,
    Amity Business School, Bhubaneswar,
    Orissa, India.

ISSN (Online): 2455-7838
SJIF Impact Factor (2017): 5.705

EPRA International Journal of

Research & Development

(IJRD)

Monthly Peer Reviewed & Indexed International Online Journal

Volume: 3, Issue:3, March 2018

Published By : EPRA Journals

CC License

BY NC ND

SJIF Impact Factor: 5.705 Volume: 3 | Issue: 3 | March| 2018 ISSN: 2455-7838(Online)
EPRA International Journal of Research and Development (IJRD)

INFLUENCE OF TEMPERATURE AND MEMBRANE THICKNESS ON THE ENERGY AND EXERGY PERFORMANCE OF SOLID OXIDE FUEL CELL

Emordi Chukwuma Onyeka[1]
[1]Chemical Engineering,. Federal University of Technology
Minna, Nigeria.

ABSTRACT

This study present the energy and exergy analysis of solid oxide fuel cell fed with methane as fuel. This analysis employs parameters such membrane thickness and temperature to determine the performance of Solid Oxide Fuel Cell in relation to cell voltage, energy and exergetic efficiency. The analysis shows that increasing the operating temperature will not always result in increase in energy efficiency and cell voltage, these cell characteristics begins to decrease at temperature above 1173 K, while exergetic efficiency increases with decreases in operating temperature. The decrease in membrane thickness leads to the increase in exergy and energy efficiency, and cell voltage. The findings of this study give better understanding on interaction of these parameters on SOFC. The model developed can serve as a valuable tool for optimizing designs.

KEYWORDS—*exergy; energy; cell voltage; solid oxide fuel cell.*

I. INTRODUCTION

The sources from which energy is derived can be categorized into three: renewable, nuclear and fossil source [1]. According to [2], since the commencement of industrial advancement, Fossil fuels have been exploited as the chief energy well. As global energy consumption increases, these fuels becomes depleted, bringing about severe energy crisis such as imbalance in demand and supply, instability of price, and variations in energy policies, and the emission of ecologically hazardous gases into the atmosphere [3]. This concern has resulted in researches in renewable and nuclear fuel [2].

According to [2, 3], Fuel Cells were acknowledged as one of the clean energy that meet the conditions of energy supply, economic development and environmental sustainability. These properties make Fuel cells (FCs) appealing compared with current energy systems: absence of irreversibility, which is present in quite a lot of convectional energy systems; greater system efficiency; its performance does not depend on system size. It has lower pollutant emissions; siting and fuel flexibility, low cost of maintenance because of the absence of moveable parts in the stacks; greater power density; and can be used for different purpose such as portable power, transportation, and stationary power [4]. Amongst the different kinds of FCs, the Solid Oxide Fuel Cell has displayed various advantages compared with the other types of FCs [5]. SOFCs can be grouped into High temperature Solid Oxide Fuel Cell (HT-SOFC), Intermediate temperature Solid Oxide Fuel Cell (IT-SOFC), and Low temperature Solid Oxide Fuel Cell (LT-SOFC.

In spite of the vast interest in SOFCs as a good energy alternative, with ability of contending with the current power sources, it is yet not available because of the lack of proper understanding of configuration and interaction of different factors that influence its operation. In this analysis, the parametric design problem of Solid Oxide Fuel Cell is solved through exergy and energy analysis of the SOFC by computer simulation to ascertain the optimal operating condition for the SOFC. The findings of this study give better understanding on interaction of these parameters on SOFC. The model developed can serve as a valuable tool for optimizing designs

II. THERMODYNAMIC OF FUEL CELL

A. Cell Voltage

The equation for SOFC cell voltage according to [6] is shown below

$$V_{cell} = V_{Nersnt} - V_{act} - V_{conc} - V_{ohm} \quad (1)$$

The electrochemical redox reaction occurring in SOFC is shown in Equation (2 – 4)

Anode: $H_2 \rightarrow 2H^+ + 2e^-$ (2)

Cathode: $2H^+ + 2e^- + \frac{1}{2} O_2 \rightarrow H_2O$ (3)

Overall: $\frac{1}{2} O_2 + H_2 \rightarrow 2H_2O$ (4)

The value of Gibbs free energy and enthalpy change for the redox reaction are -236.21 and -284.37 KJ/Mole respectively [6]. The work in carrying charge around the circuit from the redox reaction is the Gibbs free energy. Thus

$$\Delta G^0 = -2FV^o \quad (5)$$

$$V^o = -\frac{\Delta G^o f}{2F} \quad (6)$$

Equation (6) is the reversible open circuit voltage. Taking into effect the pressure, temperature and reactant concentration, the equation is modify to give the Nernst equation as shown in equation (7) [6].

$$V_{Ner\ nst} = V^0 - \frac{RT}{2F} \ln \left[\frac{a_{H2o}}{a_{H_2} a_{02}^{1/2}} \right] \quad (7)$$

Similarly, Equation (7) is expressed in relation to pressure in Equation (8)

$$V_{Nerst} = V^o - \frac{RT}{2F} \ln \left[\frac{p_{H_2 o}}{\left(p_{H_2} p o_2^{\frac{1}{2}} \right)} \right] \quad (8)$$

In real situation, part of this energy is loss as heat because of some parameter affecting the fuel cell efficiency. These parameters are the activation, ohmic, and concentration polarization [6].

Activation polarization: The quantity of energy required to initiate the electrochemical reaction. is called activation energy and relates to the energy barrier that must be exceeded before the reaction can go on [6]. According to [5], the Bolter – Volmer in equation (10), gives the equation for activation polarization

$$I = 2Io \sinh \left(\frac{nF}{2RT} V_{act} \right) \quad (10)$$

Rewritting Equation (10) gives

$$V_{act} = \frac{2KT}{nF} \sinh^{-1} \left(\frac{I}{2I_o} \right) \quad (11)$$

$$V_{act} = \frac{2RT}{nF} \left[\sinh^{-1} \left(\frac{I}{2I_{oa}} \right) + \sinh^{-1} \left(\frac{I}{2I_{oc}} \right) \right] \quad (12)$$

Ohmic polarization: This type of loss occurs because of the resistance to the flow of charges in the conductors and it is shown in equation (13) below.

$$V_{ohmic} = I R_{ohmic} \quad (13)$$

The resistance are caused by the interconnector R_i, electrodes R_{ac} , and electrolyte Re.

$$V_{ohmic} = I.(R_{ac} + Re + R_i) \quad (14)$$

Referencing [5], the electrolyte is the greatest influencing parameter in ohmic loss. Whereas the opposition to the flow of ions contributed by the others are minor and constant. The resistance is express as

$$R_{ohm} = [(0.010031 + 0.01842) \times 0.3 + \frac{0.00022}{0.3}] + R_e \quad (15)$$

[5, 7] express the electrolyte resistance as

$$R_e = 0.02481\ e10100 \left(\frac{1}{T} - \frac{1}{1273} \right) \ (\Omega/cm^2) \quad (16)$$

Therefore,

$$R_{ohm} = 0.02481\ e10100 \left(\frac{1}{T} - \frac{1}{1273} \right) + 0.0093 \quad (17)$$

Concentration polarization

This loss arise from concentration drops and restrictions of mass transfer at high current densities [8]. According to [9], the expression for concentration loss is shown in equation (18)

$$V_{con} = B\ 1n(1 - \frac{i}{i_l}) \quad (18)$$

This model has many fall back precisely in the area of SOFCs fueled with air and hydrogen mixed with other gases like CO_2 [5]. [5] Put forward an improved equation that suit the effect express in equation (19) as

$$V_{conc} = m.exp^{ni} \quad (19)$$

Substituting Equations (8), (12), (17) and (19) in Equation (1) gives the model for determining the cell voltage at different operating parameters.

$$V_{cell} = V^0 - \frac{RT}{2F} \ln\left[\frac{P_{H_2O}}{\left(P_{H_2} P_{O_2}^{\frac{1}{2}}\right)}\right] - \frac{2RT}{nF}\sinh^{-1}\left(\frac{i}{2i_o}\right) - m\exp^{ni} - \left[\frac{\delta_e}{3.58\times10^{-4}\exp\left(\frac{10100}{T}\right)} + 0.0093\right] i \quad (20)$$

B. *SOFC Efficiency*

The Maximum efficiency of fuel cell is given as:

The overall cell efficiency is the product of fuel utilization, voltage efficiency and maximum efficiency [10] as shown below

$$\eta = \eta_M \times \eta_v \times U_f \ . \quad (23)$$

III. EXERGY ANALYSIS

Exergy analysis is a technique, using the principle of conservation of energy and mass, in connection with thermodynamics second law in designing and analyzing of thermal system [4]. Exergy is the highest quantity of work that can be realized when a system is brought to equilibrium (mechanical, thermal and chemical) with the environment [2]. According to [4], the pressure P = 1.01 bar, temperature To = 298.15 K, and environment composition of 0.92% argon, 3.03 % water, 0.03 % carbon dioxide, 20.35 % oxygen, and 75.67 % Nitrogen are assumed as reference. Without magnetism, electricity, nuclear and surface tension effects, [11] defines specific molar Exergy (KJ/mol) as the summation of kinetic Exergy (ex_{ke}), chemical molar Exergy (ex_{ch}), thermal Exergy (ex_{th}) and potential Exergy (ex_{pe}), in equation (24).

$$ex = ex_{ke} + ex_{pe} + ex_{th} + ex_{ch}. \quad (24)$$

The kinetic and potential Exergy is assume negligible in this study. Thus, equation (24) is reduced to equation (25) below as given by [12].

$$ex = ex_{th} + ex_{ch} \quad (25)$$

Thermal Exergy which is also known as physical Exergy is the magnitude of work which is obtained from a flow of material brought from its initial state to the environmental (restricted) state though exchanging heat only with the environments thermal reservoir [4, 13]. The chemical Exergy according to [13] is the entire amount of work, which can be obtained from a flow of matter brought from the environment (restricted) state to the total dead (unrestricted) state while exchanging only substances and heat with the environment. [14, 4, 15] gives the equation for the chemical and thermal Exergy shown in (26) and (27) below

$$ex_{th} = (h - h_o) - T_0(S - S_0) \quad (26)$$

$$ex_{ch} = \sum x_s ex_s^o + RT_O \sum x_s . Inx_s \quad (27)$$

Where $h-h_o$ is the enthalpy change and $S-S_O$ is the entropy change. [4, 15] represent the equation as a function of specific heat as shown below :

$$ex_{th} = C_P(T - T_O) - T_O\left[C_P In\left(\frac{T}{T_O}\right) - RIn\left(\frac{P}{P_O}\right)\right] \quad (28)$$

The total specific Exergy is represented as

$$ex = C_P(T - T_O) - T_O\left[C_P In\left(\frac{T}{T_O}\right) - RIn\left(\frac{P}{P_O}\right)\right] + X_S . ex_s^o + RT_O \sum X_S . InX_S \quad (29)$$

The overall Exergetic efficiency of SOFC is calculated using the equation proposed by [2] below

$$\eta = \frac{W_{NET}}{EX_{CH}FUEL + EX_{CH}H_2O} \quad (30)$$

The mathematical model developed was simulated with the parameters given in Table 1.

Table 1 Parameters for all Simulations

Parameter	Value	Unit
Electrolyte thickness(t)	40 x 10^{-6}	µm
Fuel utilization (U_f)	0.85	
Viscocity	0.21x 10^{-6}	Kg/cm/s
Temperature (T)	800	°C
Average pore radius (r)	0.5 x 10^{-6}	m
Air utilization (U_a)	0.2	
Cathode pressure	1	Bar
Exchange current density (i_o)	1000	A/m^2
Anode pressure	1	Bar
Active surface area (A)	100	cm2

IV. RESULTS AND DISCUSSION

A. Influence Of Different Parameter on the Cell Voltage Of SOFC

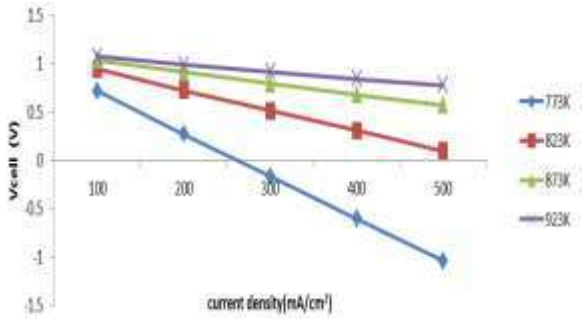

Fig. 1. Effect of Temperature on LT-SOFC Voltage

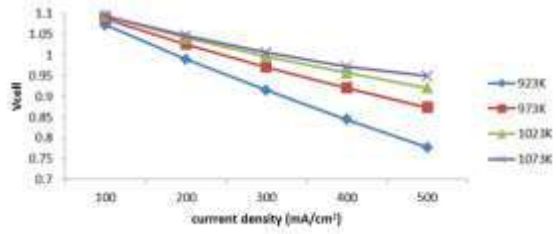

Fig. 2. Effect of Temperature on IT-SOFC Voltage

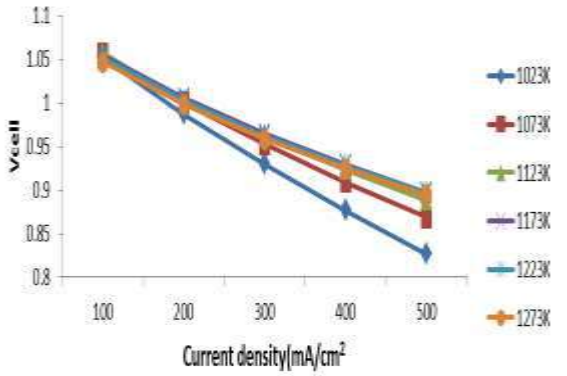

Fig. 3. Effect of Temperature on IT-SOFC Voltage

From fig 1-3, it is obvious that operating Solid Oxide Fuel Cell at high temperature results in improved cell voltage. Though there is a decrease in Nernst voltage as temperature increases, this effect seems to be completely balance as the ionic resistance also decreases. The result indicates that 1173K is the optimum temperature and the cell voltage curve behaves asymptotically at higher temperature. This evidently shows that there is no further improvement in the cell voltage with increase in cell temperature beyond the optimum value. The cell voltage is negative at temperature lower than 773K (500^{o}C), because the Solid Oxide Fuel Cell is still stabilizing. Also the cell voltage decreases with increase in current density, which is due to the increase in polarization losses.

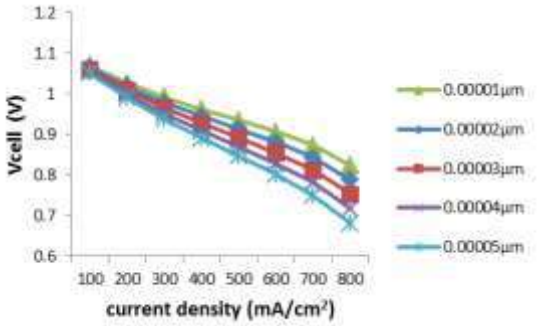

Fig. 4. Effect of Membrane Thickness on the Cell Voltage of SOFC

From fig 4, it is obvious that the voltage of the cell is greater at low membrane thickness and decreases as the membrane thickness increases. This decrease is because the Ohmic loss (opposition to the movement of current), is proportionate to the membrane thickness.

B. Influence Of Different Parameter on the SOFC Efficiency

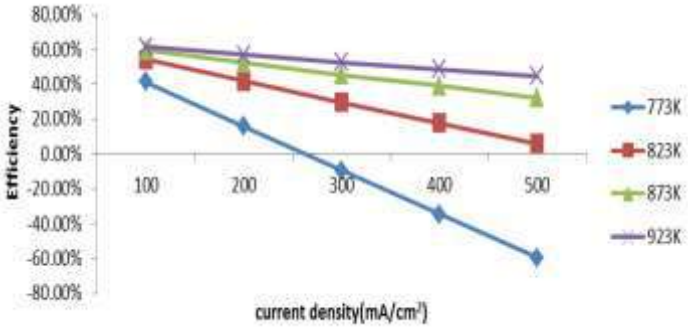

Fig. 5. Effect of Temperature on Energy Efficiency of LT–SOFC

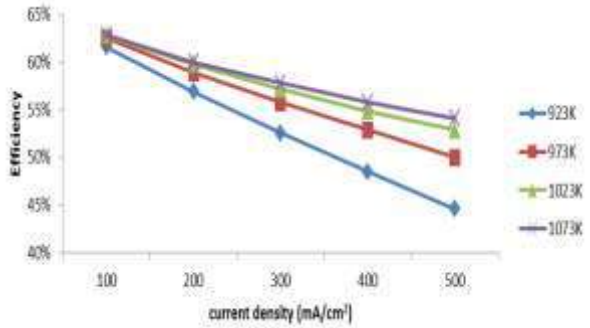

Fig. 6. Effect of Temperature on Energy Efficiency of IT –SOFC.

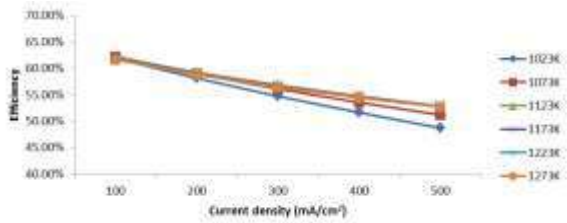

Fig. 7. Effect of Temperature on Energy Efficiency of HT –SOFC.

From Fig 5-7, it is clear that increasing cell temperature leads to increase in cell efficiency. At a temperature of 1173k, the graph indicates a maximum efficiency of 63.2%. At higher temperature, the cell efficiency decreases. Nevertheless, the cell efficiency declines as the current density rises, which is because of increase in polarization losses. At temperature value below 773K (500^{o}C) the cell efficiency is negative.

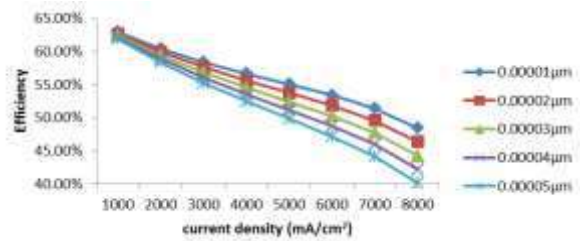

Fig. 8. Influence of Membrane Thickness on Energy Efficiency

Figure 8 illustrations the influence of membrane thickness at various current density on the SOFC efficiency. With increasing membrane thickness the cell efficiency decreases and vice versa owing to the fact that ohmic loss decreases with decrease in membrane thickness. Nonetheless, the cell efficiency decreases with increase in current density. This is because increase in current density lead to higher polarization losses.

C Influence of Different Parameter On Exergy Efficiency Of SOFC

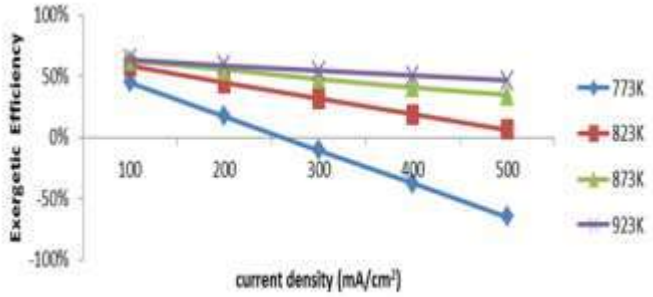

Fig. 9. Effect of Temperature on Exergy Efficiency of LT –SOFC

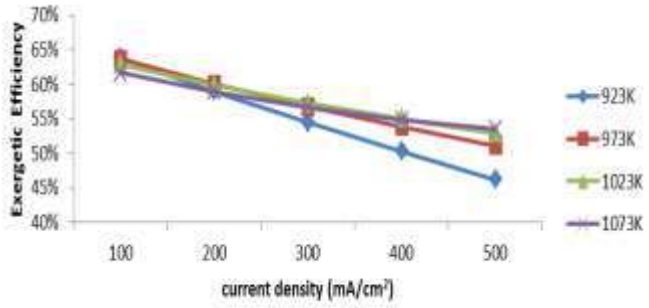

Fig. 10. Effect of Temperature on Exergy Efficiency of IT –SOFC

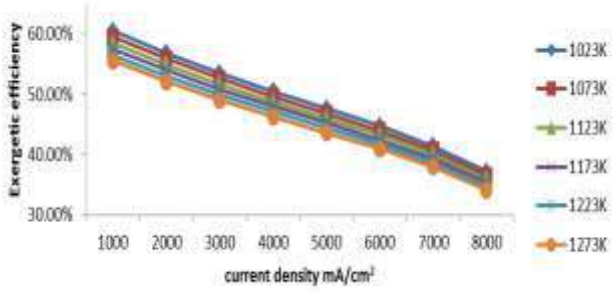

Fig. 11. Effect of Temperature on Exergy Efficiency of IT –SOFC

The effect of different temperature on the Exergy efficiency of solid oxide fuel cell by computer simulation are presented in figures 4. 9-11. The graphs reveals that the higher the cell temperature, the lower the cell exergy efficiency owing to the fact that at low temperature, exergy loss is lower

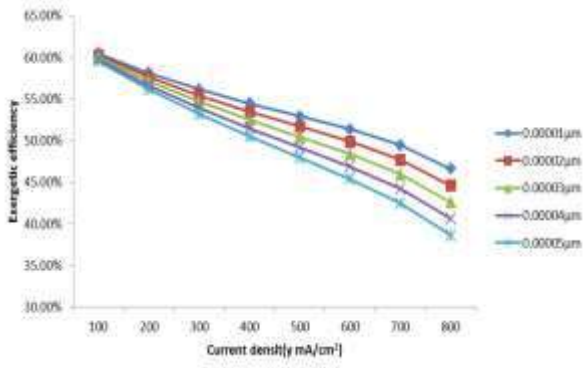

Fig. 12. Influence of Membrane Thickness on Exergy Efficiency

Fig. 12 illustrates the influence of membrane thickness at various current densities on exergy efficiency. The diagram reveals that increasing membrane thickness will lead to decrease in Exergy efficiency. This is because ohmic polarization increases with membrane thickness. Yet, the exergy efficiency decrease as the current density increases.

V. CONCLUSION

A comprehensive model was developed so as to determining the influence of different operating temperature and membrane thickness on SOFC performance in terms of energy efficiency, exergy efficiency, and cell voltage,. The result obtained shows that at a given current density, increasing the cell temperature will cause the cell voltage and energy efficiency to rise. However, at temperature exceeding 1173k the efficiency and cell voltage starts to fall. The cell voltage and energy efficiency decreases due to increase in irreversible losses as the current density increases. However, exergetic efficiency decreases with the increase in operating temperature. As membrane thickness increase at a given current density, exergy and energy efficiency, cell voltage will decrease.

ACKNOWLEDGMENT

I will like to express my appreciation to all those who contributed to the completion of this research. A special gratitude to Dr A.S Abdulkareem my Co-supervisor Chemical Engineering, Federal University Of Technology Minna, who enlighten me on how to coordinate my project. Special thanks to Caleb Adediwura for his support.

REFERENCES

1. *Xian. H., Justin. C., John. V. (1998): Types of Energy Source; Energy Matter, pp 4.*
2. *Colpan, O.C. (2009): Thermal Modeling of Solid Oxide Fuel Cell Based Biomass Gasification Systems, PhD Thesis, Carleton University Ottawa, Ontario, Canada, pp 1-55.*
3. *Abdulkareem, A.S. (2009): Design And Development Of Proton Exchange Membrane From Synthetic Rubber And Carbon Nanocells for Pem Fuel Cell, Phd Thesis, University Of Witwatersrand, South-Africa, pp 1-35.*
4. *Von Spakovsky. M. R., Nelson. D. J., Ellis. M. W., Olsommer, B., and Ogburn, M. J. (2000). A Multi- / Inter-Disciplinary Approach To Fuel Cell System Development: The U.S. DoE GATE Center For Automotive Fuel Cell Systems At Virginia Tech, Journal on Society of Automotive Engineers, Inc., pp 1.*
5. *Nguyen, D.T. and Goro, F. (2012): Advances in Natural Gas Technology: Modeling of a SOFC Power Unit Using Natural Gas Fed Directly, Dr. Hamid Al-Megren (Ed.), pp 9-20.*
6. *Jakub, .k. (2009):Considerations Regarding Modeling of Mw-Scale Ig-SOFC Hybrid Power System. PhD Thesis, RES| the School for Renewable Energy Science/University of Iceland & the University of Akureyri. Chapter 2. Iceland & the University of Akureyri. Chapter 2.*
7. *Vinod. M.j., and Olaf, D. (2006): CFD Analysis of a Solid Oxide Fuel Cell with Internal Reforming: Coupled Interactions of Transport, Heterogeneous Catalysis and Electrochemical Processes. Journal of Power Sources 162, pp 4.*
8. *Mert, S.O., Dincer, I., Ozcelik, Z. (2007): Exergoeconomic Analysis of a Vehicular PEM Fuel Cell System: Journal of Power Sources 165, pp 244–252.*
9. *Okanwanyi, J.j. (2012): Modeling And Simulation of Solid Oxide Fuel Cell, Undergraduate Research Project, Futminna Niger State, pp 5-28.*
10. *Huayang. Z. and Robert J. K. (2006): Thermodynamics of SOFC Efficiency and Fuel Utilization as Functions of Fuel Mixtures and Operating Conditions: Journal of Power Sources 161, pp 3-7.*
11. *Jamalabadi, M.Y.A., Hooshmand, P. and Broumand, B. (2004): Economic and Environmental Modeling of A Mgt-SOFC Hybrid Combined Heat And Power System For Ship Applications. Middle-East Journal of Scientific Research, 22 (4), 3.*
12. *Sreeramulu. M., Gupta. A., Srinivas. T. (2011): Exergy Analysis of Gas Turbine – Fuel cell based combined Cycle Power Plant. International Journal of Engineering Science and Technology, 3, 227-236.*
13. *Douvartzides, S., Coutelieris, F., Tsiakaras, P. (2004): Exergy Analysis of A Solid Oxide Fuel Cell Power Plant Fed By Either Ethanol Or Methane. Journal of Power Sources, 49, 3-4*
14. *Hussain. M.M., Baschuka. J.J., Li. X., Dincer. I. (2005): Thermodynamic analysis of a PEM fuel cell power system. International Journal of Thermal Sciences, 44, 3-11.*
15. *Yunus, A.C. and Michael, A.B. (2003): Thermodynamics: An Engineering Approach, Fifth Edition, chapter 8.*