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Mathematical Modeling of Solid Oxide Fuel Cell and Gas Turbine Hybrid System for Enhancing Thermal Performance

Smita Sharma and R. S. Mishra***

ABSTRACT

Fuel cell systems are environment friendly. It is a clean energy generator but it has a low efficiency when it is used alone. Gas turbine also has a lower efficiency around 30% when working alone. Hybrid system is the combination of gas turbine and fuel cell to achieve a higher efficiency around 60-70%. The fuel cell generates the major portion of the plant power output and the gas turbine generates a fraction of total power output. The major advantage of fuel cell is that it is not a heat engine so its efficiency can be 100 % as it is not limited by the Carnot efficiency. Solid oxide fuel cell (SOFC) combined with gas turbine (GT) hybrid plants produce 50 times less nitrous oxide than current conventional gas turbine and 75% less carbon dioxide than coal- fired power plants. This type of hybrid system has a wide application such as decentralised electricity supply in houses and buildings, heat and cooling energy. The present paper includes reviews of the work done in the field of SOFC/GT hybrid system, mathematical modelling using Methane as a fuel to the hybrid system is presented and future scope of work is discussed.

Keywords: *Gas Turbine; Solid Oxide Fuel Cell; Energy*.

1.0 Introduction

There is an ongoing energy crisis due to increasing use and diminishing resources of fossil fuels and another factor is environmental issues such as emission and global warming due to which people are thinking about renewable energy sources and highly efficient energy conversion system. Fuel cells have the potential for high energy conversion. The latest type and probably the best suited for central power generation is the solid oxide fuel cell (SOFC). These cells use a solid ceramic electrolyte of yttrium zirconium which the operating temperature ranges from about 600 to 1000 °C. Hybrid system uses a high temperature fuel cell and gas turbine to achieve higher overall performance than a single mode power plant. Heat can be recovered from the high temperature exhaust gas and used to drive a gas turbine. In the gas turbine exhaust gases expand and produces additional power. This hybrid system is a combination of two systems. One is gas turbine which acts as a heat engine. The other one is fuel cell which is a non heat engine. The efficiency and the performance of this hybrid system are far better than provided by either system alone. Basically in this hybrid system coupling of fuel cell and gas turbine is performed for power generation. Coupling can be performed by two methods by indirect method or integration of a micro gas turbine and SOFC by a heat exchanger and by direct method or integration of micro gas turbine and fuel cell directly.

2.0 Literature Review

Feasibilities of SOFC/GT hybrid systems have been investigated by numerous researchers. R. A. Roberts and J. Brouwer [1] compared and presented the Results of the dynamic model and experimental data gathered during the operation and testing of the 220kW SOFC/GT at the National Fuel Cell Research Center. Shinji Kimijima and Nobuhide Kasagi[2] investigated a conceptually designed 30 kW capacity SOFC/GT hybrid micro generation system and Result shows that variable speed mode is more advantageous to performance degradation under pert load condition Denver F. Cheddie,

**Corresponding Author: Laser Science and Technology Centre (LASTEC), DRDO, Metcalfe House, New Delhi, India (E-mail: professor_rsmishra@yahoo.co.in)*
***Department of Mechanical Engineering, Delhi Technological University, Delhi, India*

Renique J Murray [3] developed a thermo-economic model for the hybrid power plant, and predicts an optimized power output of 20.6 MW at 49.9% efficiency. Sordi, E. P. da Silva, A. J. M. Neto, D.

G. Lopes, C. S. Pinto, P. D. Araújo[4] presented a methodology to simulate a small-scale fuel cell system for power generation using biomass gas as fuel. The comparison with the efficiency of simple gas turbine cycle and regenerative gas turbine cycle shows the superiority of SOFC for the considered electrical power range. Leto, Celidonio Dispenza, Angelo Moreno, Antonio Calabr`o [5] performed the steady state simulation of the Hybrid System shown that the efficiency both of the Electrochemical Unit and of the whole Hybrid System can be higher than that of gas –steam turbine conventional power plant. The overall electrical efficiency could reach a very high value (up to 60%) and total efficiency could be over 70% including the contribution due to heat recovery. Sivan Kartha, Thomas G. Kreutz, and Robert H. Williams [6] calculated the total system efficiency of a power plant in which the fuel cell accounts for approximately three quarter of the generated power (149 kW) and the gas turbine one quarter (50 kW) based upon electrical output of the design. It was calculated to be 43.4%. Senthil V. Vannivedu Umapathi, Kiran Rao Bhimma and Parchuri M. V. Subbarao[7] successfully modeled methane fed hybrid SOFC-GT power generation system of 1.25 MW capacities. It has been demonstrated that SOFC-GT can achieve 60% net electrical efficiencies. Xiao-Juan Wu, Qi Huang Xin-Jian Zhu [8] proposed a least square support vector machine (LS—SVM) identification model based on a improved particle swarm optimization (PSO) algorithm to describe the nonlinear temperature dynamic properties of the SOFC/MGT hybrid system. A SOFC/MGT physical model is established via Simulink toolbox of MATLAB6.5. Compared to the conventional BP neural network and the standard LS-SVM, The simulation results show that the modified LS-SVM model can efficiently reflect the temperature response of the SOFC/MGT hybrid system. Rama S.R. Gorla, Shantaram

S. Pai and Jeffrey J. Rusick [9] performed a probabilistic analysis of SOFC/GT hybrid system. The cycle achieved a thermal efficiency of 64.1 percent at a pressure ratio of 14. The specific power output was found to be 520 W/kg s. Said Al-Hallaj, Fuad Alasfour, Sandeep Parekh, Shabab Amiruddin, J.Robert Selman, Hossein Ghezel-Ayagh[10] proposed and investigated a novel concept for integrating fuel cells with desalination systems . Results indicate that such hybrid system could show a 5.6% increase in global efficiency. Bang-Møller Christian, Rokni Masoud [11] presented a system level modelling study of three combined heat and power systems based on biomass gasification. By combining the SOFC and MGT, the unconverted syngas from the SOFC is utilized in the MGT to produce more power and the SOFC is pressurized, which improves the efficiency to as much as 50.3%.

A clean method of power generation is electrochemical extraction of energy from hydrogen via fuel cell. This technology is very suitable for a post fossil fuel based energy economy. But transition from the fossil fuel to hydrogen based system will take time and it is complicated also. There are various types of fuel cell in which solid oxide fuel cell is well suited. The operating temperature of SOFC is very high which facilitates the combination with gas turbine to reach electrical efficiencies beyond the limitations of conventional technologies. Fuel cell is well suited for distributed power generation as it can achieve higher efficiency even for small units. An experimental investigation of this system for design and performance evaluation is very expensive so mathematical modelling of the system and its simulation proves to be inexpensive. In present paper Mathematical modelling is presented for SOFC/GT hybrid system.

3.0 System Configurations

A schematic diagram of the tubular SOFC/GT hybrid power system using methane as fuel is given in Fig.1. The compressed methane is heated in heat exchanger. In the internal reformer, methane is reformed by using steam and heat from the SOFC. Reforming reaction is as follows:

$CH_4 + H_2O = CO + 3H_2$ & $Co + H_2o = CO_2 + H_2$

The Productions of reforming reaction are then fed to anode of SOFC. Ambient air is compressed by a compressor which is driven by a turbine and then heated in the heat exchanger by the hot gas stream from the turbine exhaust. The hot, high-pressure compressed air is then fed to the cathode section of SOFC. Natural gas and air are streamlined and passes through the anode and cathode sections respectively. The electrochemical reaction results into production of electrical energy and heat. The heat used to reform the natural gas and partly used to heat up the feedstock gases. The high temperature and pressure combustion products are channelled to turbine. In turbine, expansion occurred and pressure and temperature are reduced.

The specification of hybrid system components are given in Table 1. The turbine outlet has high temperature and it can be used for increasing of compressor outlet in heat exchanger. Fuel cell electrochemical reaction is as

½ $O_2+2e^-=O^{-2}$ Cathode $H_2+O^{-2}=H_2O+2e^-$ anode

$H_2+1/2O_2=H_2O$ Overall reaction

Fig 1: Schematic Diagram of the Tubular SOFC/MGTHybrid Power System [14]

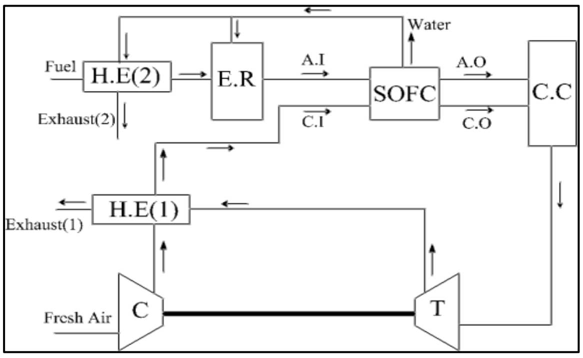


Table 1: Specification of the Hybrid SOFC/MGT System[14]

Fuel Inlet Temperature (°C)	20	SOFC Temperature (°C)	800
Fuel Inlet Pressure (kpa)	300	SOFC Pressure (kpa)	300
Air Inlet Temperature(°C)	20	Air Inlet Pressure (kpa)	100
Cell Area (cm^2)	130	Number Of Cells	120
External Reformer Efficiency (%)	80	Air Stoich	6
Internal Reformer Efficiency (%)	80	Combustor Isentropic Efficiency%	98
Compressor Isentropic Efficiency%	87	Combustor Pressure drop%	4
Turbine Isentropic Efficiency (%)	89		

4.0 Over-Potentials in SOFC

Due to irreversibility in the cell operation, the cell voltage, V, is always lower than reversible voltage E. This difference termed polarization and is the sum of three types of losses including, activation, ohmic and concentration.

(1) Activation Losses:

The energy barrier between the electrode and electrolyte results in a loss known as activation loss, significant at low currents. The activation overvoltage is calculated using the Butler–Volmer equation [12],

$i=io[\exp(\alpha nF/RT \; xVact)- \exp(-(1-\alpha)nF/RTx \; Vact)]$

$Vact=RT/Fxsinh\_1 (i/io)$

Where α is the charge exchange constant and *io* is the exchange current density.

(2) Ohmic Losses:

The ohmic losses are calculated from following equation:

$Vohm=I\Sigma j[Aj\exp(Bj/T)x\delta i]/Asj$

A, B, δ are the constants which can be taken from [13],

(3) Mass Concentration Losses:

$Vcon=(RT/2F)\ln(1-i/il)$

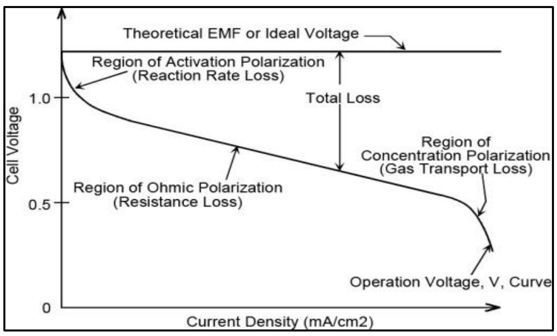
Where i is the current in the fuel cell and il is the limiting current in that cell. Vcell = E − Vohm − Vconcetration – Vactivation

$PSOFC = nIVcell$

Then the net power from the hybrid SOFC/MGT system is determined by

$Pnet + PSOFC + Pturbine + Pcompressor$

Fig 2: Polarization Curve [12



5.0 Result

The effects of pressure of the cell voltage are shown in Fig.3.Improvment in the yield of the cell at higher current densities is clearly visible from the figure.

By increasing the fuel mass flow rate, the output current value of the fuel cell increases therefore output power of the cell will be reduced.

By increasing the fuel flow rate and therefore flow rate passing through the turbine, the power will increase.

Fig 3: Polarization Curve at Different Current Density [14]

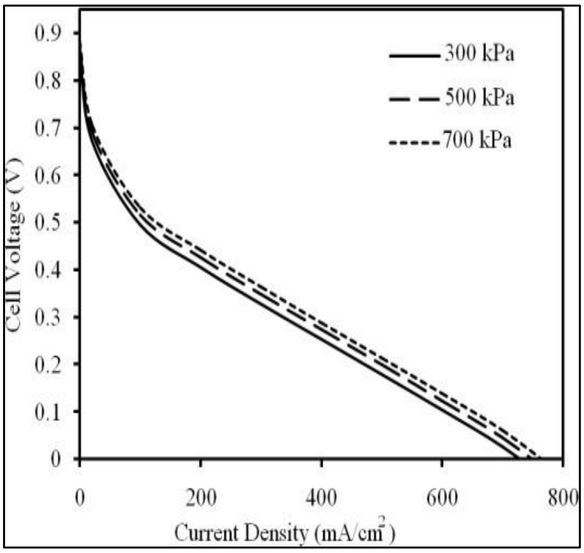


Fig 4(a) : Power Produced by SOFC/MGT at DifferentCurrent Densities. [14

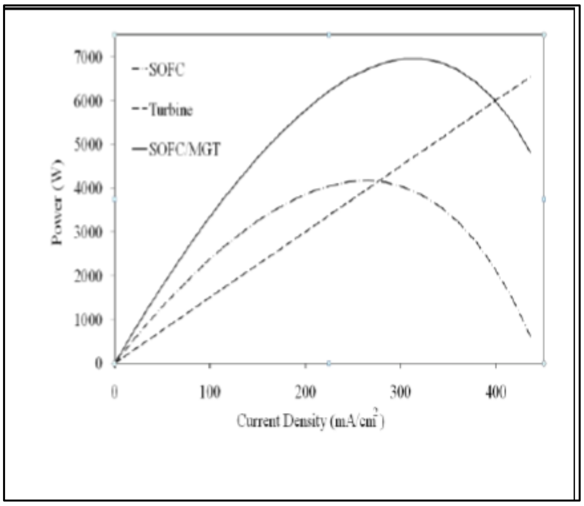
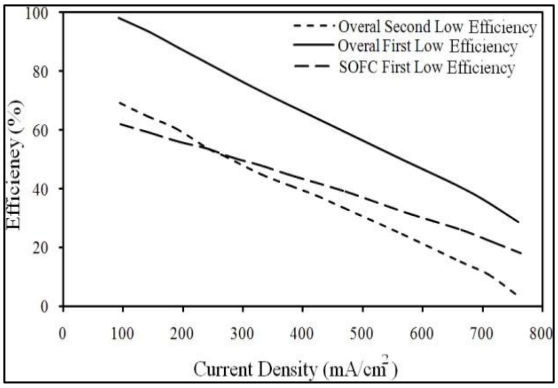


Fig 4(b) : Efficiency Produced by SOFC/MGT at DifferentCurrent Densities. [14]



6.0 Conclusions

In this paper, a review study was performed to assess various SOFC/GT hybrid systems. Effect of parameters on performance of a hybrid SOFC/MGT power system was observed. The parameters studied include temperature, pressure, the cathode flow rate, the anode flow rate, and percentage of fuel use. Power production and the first and second law efficiencies of the hybrid SOFC/MGT systems were observed from the literature. It is observed that simulation methods to simulate the SOFC/GT hybrid system are few. It is required to develop a mathematical model and simulate that model by using suitable simulation software.

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