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Design and Modeling of 10KW Biofuel Based Solid Oxide Fuel Cell System

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Abstract: ***With the objective to implement clean, efficient and environmentally friendly technology for electricity generation, the design of a biofuel based SOFC system of 10kW is proposed and modeled theoretically. In particular the focus of this paper is on the modeling of a stack design of biofuel based solid oxide fuel cell system. A lumped parameter modeling approach is implemented in this paper in which all the fundamental equations of fuel cell losses and efficiency are considered for better characterization of the system. On the basis of single cell performance a stack cell system of 10kW along with polygeneration applications is analyzed by different performance curves of stack system including electrical efficiency, heating efficiency, combined heating and power efficiency (CHP), combined cooling and power (CCP) efficiency and combined cooling heating and power (CCHP) efficiency are plotted for different temperature ranges, fuel utilization factor and operating pressure of the system. All the analysis and implementation of system is incorporated in MATLAB software.***

Keywords: Polygeneration, Stack, Lumped, SOFC, Biofuel

1. Introduction

Energy woes of Pakistan have become so visible recently that the whole country has been feeling the brunt of it. Economic development of a country depends on the availability of cheaper energy. Utilization of renewable energies is of major importance because of the increase in fossil energy costs in combination with carbon dioxide reduction prevent global warming. Renewable energy is generated from natural resources such as sunlight wind, water, tides, and various forms of biomass.

Hydrogen fuel cell technology provides a promising way to both address the environmental concerns and to find more efficient use of disappearing fossil fuels. Fuel cells are electrochemical devices that generate electrical power by continuously converting chemical energy of supplied fuel into electrical energy through an electrochemical reaction and it's by products are water and heat. Having their clean and efficient nature of reaction fuel cells are recognized as the environmental friendly source of energy. Fuel flexibility, low emission rate and high chemical to electrical energy conversion efficiency has made the fuel cell technology viable and the most promising technology to cope with the future energy crisis of electricity with decreased environmental hazards [1][2].

Among various types of fuel cells developed solid oxide fuel cell (SOFC) are attracted to researchers because of their high energy conversion efficiency and is one of the most efficient fuel cell which operates at high temperatures (800-1000C^o) for conversion of hydrogen fuel energy into electrical energy. SOFCs have the ability to run on variety of hydrocarbon fuels such as gasoline, diesel, natural gas and biofuels. Their potential applications range from few watts to megawatts. High operating temperature has some disadvantages including potential thermal fatigue of the cell material and sealing under the high temperatures [3][4]. Recent researchers in reference paper [5] have given much improvement in reducing the temperature (400-600C^o) and lowering the manufacturing cost.

The combination of biogas and a solid oxide fuel cell (SOFC) is a promising method of chemical to electrical power conversion with reduced greenhouse gas emissions. Biogas is produced during anaerobic digestion of biological matter, which can be produced from various sources such as dairy forms, human waste, animal wastes and landfills [6].Fuel cells compared with other possible prime movers are one of the most suitable candidates for the polygeneration systems. Polygeneration systems refer to simultaneous production of power and one or more side products like space heating, water heating and cooling from single fuel source [7].

As the real systems are very expensive so before implementation modeling is essential. Modeling is a useful tool for practicing new ideas and to analyze the hypothetical behavior of real system. Different modeling approaches are available in literature [8] [9] [10]. Here in this paper lumped parameter modeling technique is implemented which considers the fuel cell as a single lumped system which reduces the complexity and computation time. In lumped system species enter the cell through one side and leaves through the other end. Different recently used lumped parameter models are available in literature [11].

All the single cell results are considered from reference paper [7] and modified for biofuel based 10KW system. According to experimental results of [7] the cell operating voltage and current density are (0.6) V and (550) Acm^{-2} respectively. The input parameters, biogas composition and output calculated results of the proposed system are given in table1, table2 and table4 respectively.

2. System Design and Modelling

2.1 System Design

The schematic diagram of the proposed SOFC system design is shown in figure (1).

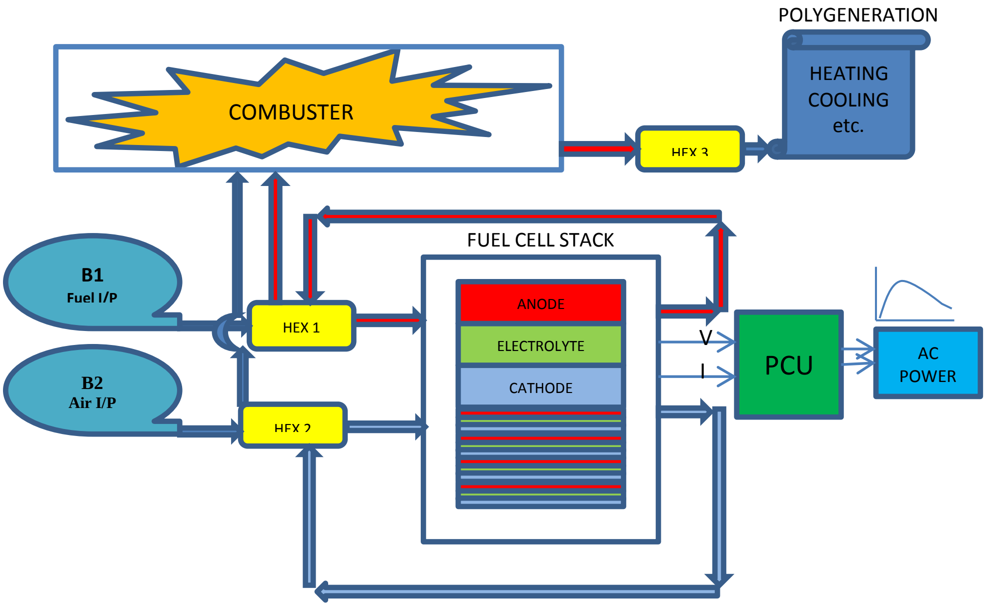

Figure 1: Schematic of SOFC System

The system consists of SOFC stack, combustor, heat exchangers, blowers (B1 and B2) and power conditioning unit (PCU). All the components are equally important and have to be considered for the prediction of efficiency and performance of the SOFC power generation system. Biogas from Fulani cow having composition in table 3 from reference paper [12] is used as input fuel to the system. A preheated air at cathode side is used as an oxidant and preheated biofuel is fed at anode side and an electrochemical reaction takes place at boundaries of electrolyte and both the electrodes to produce electricity, water and heat. The dc electrical power from fuel cell stack output is further brought to power conditioning unit (PCU) to convert dc power into desired AC electrical power. The unreacted fuel at the outlet of fuel cell stack and exhaust gases are further brought to combustor chamber through exhaust streams to burn them and extract more useful heat to be used in heat exchanger 1 and heat exchanger 2 to preheat the air and fuel at the input and also in heat exchanger 3 for polygeneration applications such as heating, cooling and domestic water heating etc.

2.2 Modeling

Modeling of fuel cell voltage constitutes four voltages. Voltage of the SOFC is obtained by subtracting the losses containing activation (V_{act}), concentration (V_{con}), and ohmic (V_{ohmic}) from open circuit voltage or no loss voltage called E_{nernst} of the cell. The voltage equations of the fuel cell can be expressed as. [9]

$$V_{fc} = E_{nernst} - \text{losses} \quad (1)$$

$$\text{Losses} = V_{act} + V_{con} + V_{ohmic} \quad (2)$$

$$V_{fc} = E_{nernst} - V_{act} - V_{con} - V_{ohmic} \quad (3)$$

The instantaneous electrical power supplied by the cell to the load can be expressed as [1]

$$\text{Power, } P_{fc} = V_{fc}.\, I \quad (4)$$

Where V_{fc} is the cell output voltage and P_{fc} is the output power, in Watts.
For stack of n cells, power of the system will be expressed as

$$\text{Power, } P = n\,(V_{fc} * i) \quad (5)$$

Where n is the number of cells in the stack.

Table 1: Input Parameters of System

Operating temperature (C)	600
Operating pressure (bar)	1
Fuel utilization factor (%)	85
Air stoichiometric ratio	2
Operating voltage of cell (V)	0.6
Nominal power (KW)	10
Cell active area (cm^2)	150
Ambient temperature	25
Heat Exchanger Effectiveness (%)	85
Blower isentropic efficiency (%)	83
Power conditioning unit efficiency (%)	95

Table 2: Biogas Composition [12]

CH_4 (%)	85.331
CO_2 (%)	13.011
N_2 (%)	1.596
CO (%)	0.13
Air $_{(N+O)}$ (%)	0.048

2.2.1 Nernst Reversible Voltage

The Nernst reversible voltage is the open-circuit voltage or no loss voltage of the fuel cell given by equation below. The equations of E_{nernst}, V_{act}, V_{con} and V_{ohmic} are available in [1][9][13][14] and [15]. All parametric constants of the modeling equations used in the system are given in table 3.

$$E = E^0 + \frac{RT}{nF}\ln\left(\frac{Ph_2.Po_2{}^{0.5}}{P_{h_2}O}\right) \quad (6)$$

Where E^0 is the standard cell potential, Ris the universal gas constant, Tis the operating temperature of the fuel cell, F is faraday's constant, and Ph_2 is the hydrogen partial pressure,

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Ph_2o is the water partial pressure and Po_2 is the oxygen partial pressure.

2.2.2 Activation loss

Chemical reactions, including electrochemical reactions, must overcome energy barriers, called “activation energy,” for the reaction to proceed. This leads to activation polarization and is caused by slowness of electrochemical reactions given by equation.

$$V_{act} = a + b\log(i) \tag{7}$$

Where, $a = -2.3\frac{RT}{n\propto F}\log(io)$, $b = 2.3\,\frac{RT}{n\propto F}$

Where i_o is the exchange current density, α is the coefficient of charge transfer and n is the number of moles of electrons transferred. The equations of i_o, $i_{o,a}$, $i_{o,c}$ from [14] are given below.

$$i_o = \gamma\left(\frac{P_r}{P_r^{ref}}\right)^m \exp\left(-\frac{E_c}{RT}\right) \tag{8}$$

Where γ is pre-exponential factor of the electrode, P_r is reactant partial pressure in kpa, P_r^{ref} isreference pressure at the corresponding electrode in kpa, m is pressure coefficient, $E_c$is activation energy at the corresponding electrode kJ/mol. Now exchange current densities at both the electrodes are expressed below [14].

$$i_{o,a} = \gamma_a\left(\frac{P_{H_2}}{P_{H_2}^{ref}}\right)\left(\frac{P_{H_2o}}{P_{H_2o}^{ref}}\right)\exp\left(-\frac{E_{c,a}}{RT}\right) \tag{9}$$

$$i_{o,c} = \gamma_c\left(\frac{P_{O_2}}{P_{O_2}^{ref}}\right)^{0.25} \exp\left(-\frac{E_{c,a}}{RT}\right) \tag{10}$$

2.2.3 Ohmic loss

The ohmic overpotential result from ionic resistance in the electrolyte and electronic resistance in the electrodes, bipolar plates and terminal connections, can be expressed as

$$V_{ohmic} = i.R_{tot} \tag{11}$$

Where R_{tot} is the sum of the individual resistance of each component of the fuel cell given by the expression below

$$R_{tot} = \rho_e\sigma_e + \rho_a\sigma_a + \rho_c\sigma_c + \rho_i\sigma_i \tag{12}$$

Where $\rho_e, \rho_a, \rho_c, \rho_i$ and $\sigma_e, \sigma_a, \sigma_c, \sigma_i$ are resistivities and thicknesses of electrolyte, anode, cathode and interconnect respectively.

2.2.4 Concentration Voltage Loss

This occurs due to the mass transfer resistance to the flow of the reactants and the products through the porous electrodes. Concentration voltage loss can be calculated as

$$V_{con} = m.\exp(ni) \tag{13}$$

Where the typical values of m and n are 3 x 10^{-5}V and 8x10^{-3}cm^{2}mA^{-1} respectively. The efficiency of the system can be calculated from equation available in literature [7][13].

$$\eta_{Sofc} = \frac{P_{el}}{Q_{fuel}} \tag{14}$$

$$Q_{fuel} = m_{fuel}.LHV_{fuel} \tag{15}$$

Where Q_{fuel} is the amount of energy entered in the cell through fuel.and m_{fuel} is mass flow rate of fuel and LHV is lower heating value of the fuel fed.

Similarly heat generation from stack of n cells is given by in literature [13]

$$\text{Heat generated} = n.I\,(1.25 - V_{cell})\ \text{Watt} \tag{16}$$

Table 3: Input Parametric Constants [16]

ρ_a KΩ-cm	(-0.0049 x log(T) + 0.6975) x 10^{-3}
ρ_c KΩ-cm	(-0.0049 x log(T) + 0.6975)x 10^{-3}
ρ_e KΩ-cm	(-3.57 x log(T) + 26.822)x 10^{-3}
ρ_i KΩ-cm	0.00298 exp(-1329/T)
σ_a mm	0.2
σ_c mm	0.15
σ_e mm	0.1
$\sigma_i$mm	2
Υ_a A.m^{-2}	7 x 10^5
Υ_c A.m^{-2}	7 x 10^5
$E_{act,a}$ KJ.mol^{-1}	67.54
$E_{act,c}$ KJ.mol^{-1}	67.54
R J/mol.K	8.3145
F C/mol	96485
A	0.5
N	2

3. Results and Discussion

The proposed design of the SOFC system is modeled using MATLAB software. Considering the experimental results for a single solid oxide fuel cell fabricated and investigated in [7]. The system is modeled at 600C° using a biogas of Fulani cow from [12] having the composition as described in table2. The system performance in terms of efficiency is analyzed when subjected to different temperature ranges, fuel utilization factor and operating pressures as shown in figure2 to figure7. Increasing the temperature from 600C° to 700C° figure2 shows that electrical efficiency remains almost same because of desired output power of the system is fixed to 10(KW). The heating efficiency increases prominently because extra amount of heat is available in combustor through exhaust pipe, as a result combined cooling power efficiency CCP, combined heating power efficiency CHP, and combined cooling, heating and power efficiency CCHP increases gradually as shown in figure3. Increasing fuel utilization factor increases electrical efficiency because with increase in fuel utilization factor for fixed output power less amount of fuel is required so less amount of unused fuel transferred to the combustion chamber hence less heating efficiency is observed in figure4. Similarly figure5 shows decreasing trend in CCP, CHP and CCHP. The results for third parameter of operating pressure are shown in figure6 and figure7 increasing operating pressure increases the temperature of exhaust gases so extra amount of heat is available in heat exchangers increases the heating efficiency but at higher pressure, increase in air and fuel blower power compromises fuel cell electrical efficiency as well as combined efficiencies.

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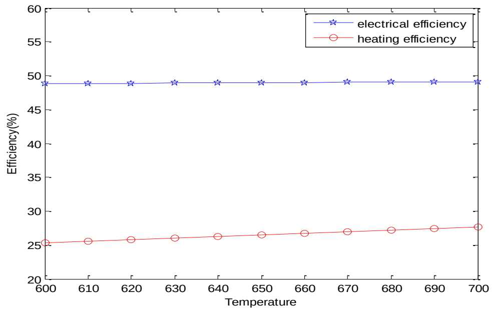

Figure 2: Temperature versus Efficiencies of the system

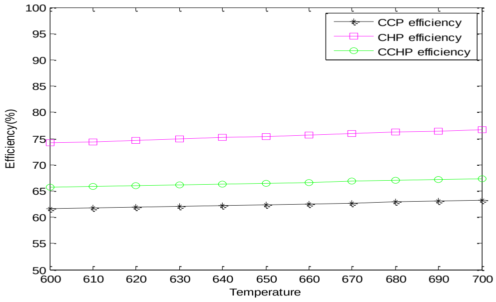

Figure 3: Temperature versus Combined Efficiencies of the system

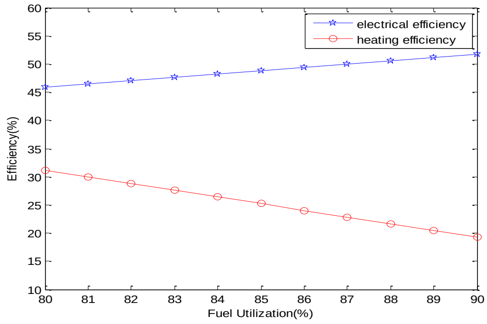

Figure 4: Fuel utilization versus Efficiencies of the system

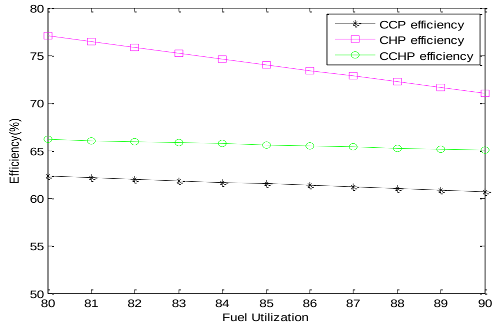

Figure 5: Fuel utilization versus Combined Efficiencies of the system

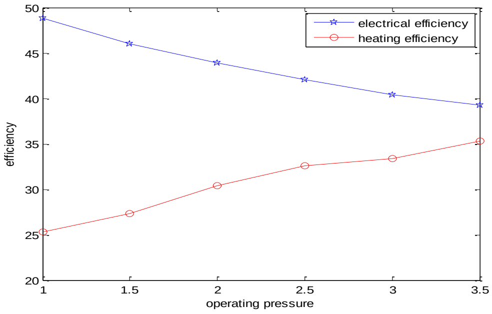

Figure 6: Operating Temperature versus Efficiencies of the system

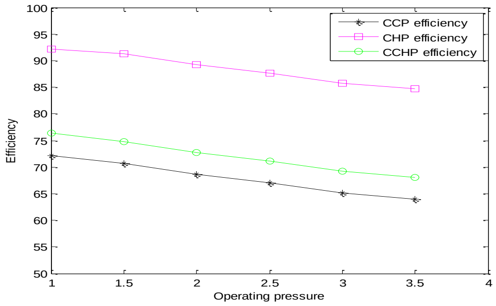

Figure 7: Operating Temperature versus Combined Efficiencies of the system

Table 4: Output Parameters of System

Output DC electrical power(KW)	9.98
Output AC electrical power(KW)	9.48
Electrical efficiency (%)	48.83
Heating efficiency (%)	25.32
CCP efficiency (%)	61.57
CHP efficiency (%)	74.15
CCHP efficiency (%)	65.66
No. of cells	210

4. Conclusion

In this paper a simple 10KW design of fuel cell system with polygeneration applications is proposed and modeled in MATLAB. At different temperature, fuel utilization factor and operating pressures efficiency plots of the system were obtained. A typical lumped parameter model is used for system modeling. Biogas as input fuel to the system at 600C^o is used to analyze the system efficiencies including electrical efficiency heating efficiency and also combined efficiencies of heating, cooling and power. The biogas of high methane content shows better results for improving electrical efficiency to 48.83% which is greater than electrical efficiency in literature [7].

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