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PERFORMANCE ANALYSIS AND SIMULATION OF FUEL CELL SYSTEM

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Abstract - *Fuel cell may become the answer for an emission free power source in future. Their ability to produce electricity can be utilized in various fields. A fuel cell can produce electricity for an unlimited period of time until fuel is supplied to it. The main fuel used as input to the fuel cell is hydrogen. Fuel cell show great potential due to their zero or low emission, high efficiency and flexible structure. This paper presents the performance analysis and simulation of the fuel cell system. A single cell cannot supply the essential power required for any application. Hence the fuel cell stacks are used. The effects of different operating parameters namely operating temperature, hydrogen and oxygen inlet pressure, cell active area are analyzed using MATLAB platform. Mathematical modelling of fuel cell is described in this paper as they are the necessary tools required for designing and various calculation of the fuel cell system. Based on the performance analysis done in this paper modelling of the fuel cell system is developed with the help of MATLAB/SIMULINK software. The simulation studies have been carried out to verify the system performance.*

Key Words: **Current density, Fuel cell, Performance, Simulation, Voltage.**

NOMENCLATURE

R	Universal gas constant (J/K.mol)
F	Faraday's constant (C)
ΔG	Change in Gibb's free energy (J/mol)
ΔS	Change in entropy (J/mol)
T	Operating temperature of fuel cell (K)
T_{ref}	Reference temperature (K)
P_{H_2}	Partial pressure of hydrogen (atm)
P_{O_2}	Partial pressure of oxygen (atm)
$\xi_1, \xi_2, \xi_3, \xi_4$	Experience parameters used in activation voltage drop
CH_2	Concentration of hydrogen
CO_2	Concentration of oxygen (mol/cm³)
i_{FC}	Fuel cell current (A)
ρ_m	Specific resistivity of membrane (Ω.cm)
A	Active cell area (cm²)
l	Thickness of membrane (cm)
J	Current density of cell (mA/cm²)
J_{max}	Maximum current density (mA/cm²)
B	Parametric coefficient
V_{st}	Stack output voltage (V)
N	Number of cells
P	Power of fuel cell (W)
V_{FC}	Fuel cell voltage (V)
E_{nernst}	Nernst voltage (V)
V_{act}	Activation voltage (V)
V_{ohmic}	Ohmic voltage (V)
V_{con}	Concentration voltage (V)
R_m	Impedance of membrane (Ω)
R_c	Impedance that block proton transfer (Ω)

1. INTRODUCTION

Increased energy consumption and global pollution have become a major problem in today's world. This has led to the search of other energy sources which will solve the present environmental problems. Fuel cell can be considered as one such example of energy source. Fuel cell systems have attracted a viable interest in distributed power generation, for hybrid vehicles etc.

Fuel cell is device which produces electricity through electrochemical reaction. Through the reaction the chemical energy is directly converted to electrical energy. In the reaction the hydrogen and water are combined to form water and heat as by-products. Electricity is produced due to external supply of fuel.[1]

Fuel cells were first developed by Sir William Grove, a British lawyer and scientist. He found the principle by accident in an electrolysis experiment. When he was performing the experiment he noticed that when the electrodes were connected, the current flew consuming hydrogen and oxygen. He named his device as 'Gas battery'. Then a century later, Francis Bacon a chemical engineer in 1950s produced the first practical fuel cell. In 1960s, the International Fuel Cells in Windsor, Connecticut, USA developed Alkaline fuel cell for NASA.[2]

Fuel cells usually use hydrogen as the fuel. There are numerous methods which can be used to produce hydrogen for a fuel cell. Based on the method used for hydrogen production, a fuel cell can either be renewable or non renewable source of energy [3]. The various methods include

1. Hydrogen production by reforming natural gas.
2. Conversion of coal.
3. H_2 production by use of nuclear energy.
4. Electrolysis of water.
5. Production from biomass.

Here the system is considered to be renewable source.

2. BASICS OF FUEL CELLS

Fuel cells consist of anode, cathode and an electrolyte. Hydrogen is fed to the anode where hydrogen molecule is spit into protons and electrons with the help of a catalyst for faster reaction. The protons move to cathode from the anode through the electrolyte and reach the cathode, but the electrons cannot pass through the electrolyte [4].The electrons travel through an external circuit producing electricity and they combine with the protons from anode and oxygen molecules supplied from surrounding in the cathode to produce water.

The chemical reaction inside a fuel cell can be broken down into two half reactions, the oxidation half reaction and the reduction half reaction. The oxidation half reaction represents the spitting of hydrogen molecule into protons and electrons which is shown in equation (1). The reduction half reaction shows the recombination of hydrogen protons with electrons and oxygen from atmosphere which is shown in equation (2). The basic working of a fuel cell is shown in Fig-1.

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$ (1)

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

Overall reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (3)

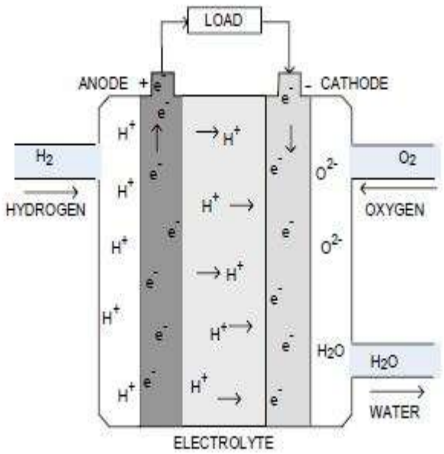

Fig-1: Basic working of a fuel cell with protons flowing through electrolyte.

3. MATHEMATICAL FORMULATION

The output voltage for a fuel cell is denoted by

$$V_{FC} = V_{rev} - V_{irr} \quad (4)$$

where V_{FC} is the fuel cell voltage; V_{rev} is the reversible voltage and V_{irr} is the irreversible voltage. Eq(4) can also be written as

$$V_{FC} = E_{nernst} - V_{act} - V_{ohmic} - V_{con} \quad (5)$$

where E_{nernst} is the thermodynamic potential of the cell and it serves as the reversible voltage. V_{act} is the activation over potential, V_{ohmic} is the ohmic voltage drop and V_{con} is the concentration voltage drop. These three voltages together are the irreversible voltages. The four voltages mentioned are function of fuel cell temperature and/or pressure and load current. These voltages and power generated are discussed in the following sections.

3.1 Reversible Voltage

The cell reversible voltage(E_{nernst}) is the potential of the cell which is obtained in open circuit condition. It is a function of temperature and pressure. E_{nernst} is calculated taking into account the change in temperature with respect to standard reference temperature. It is given as

$$E_{nernst} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}(T - T_{ref}) + \frac{RT}{2F}\left[\ln(P_{H_2}) + \frac{1}{2}\ln(P_{O_2})\right] \quad (6)$$

By using the standard values of ΔG, ΔS and T_{ref} Equation(6) can be simplified as

$$E_{nernst} = 1.229 - 0.85 * 10^{-3}(T - 298.15) + 4.31 * 10^{-5}T\left[\ln(P_{H_2}) + \frac{1}{2}\ln(P_{O_2})\right] \quad (7)$$

3.2 Irreversible Voltages

The irreversible voltages are V_{act}, V_{ohmic} and V_{con}. These are discussed below.

3.2.1 Activation Voltage Drop

It is the voltage drop due to the activation of anode and cathode. It is the measure of drop of voltage associated with the electrodes. It can be given as

$$V_{act} = -[\xi_1 + \xi_2.T + \xi_3.T.\ln(CO_2) + \xi_4.T.\ln(i_{FC})] \quad (8)$$

where ξ_1 , ξ_2 , ξ_3 and ξ_4 are experience parameters; CO_2 is the concentration of oxygen in the catalytic interface of cathode. It is a function of cell temperature which is expressed as

$$CO_2 = \frac{P_{O_2}}{5.08*10^6*e^{\left(\frac{-498}{T}\right)}} \quad (9)$$

3.2.2 Ohmic Voltage Drop

The ohmic voltage drop results from the resistance of conduction of protons through the electrolyte and electrons through its path. V_{ohmic} mainly consist of two voltage drops caused by impedance of cell. These two voltage drops are equivalent to impedance of proton membrane (R_m) and impedance that blocks the transfer of protons through membrane(R_c). The equation for V_{ohmic} is expressed as

$$V_{ohmic} = i_{FC}R_{ohmic} = i_{FC}(R_m + R_c) \quad (10)$$

The proton exchange membrane impedance is

$$R_m = \frac{\rho_m . l}{A} \quad (11)$$

where ρ_m is the specific resistivity of the membrane for the electrons to flow.

The expression for ρ_m is described as

$$\rho_m = \frac{181.6[1+0.03\left(\frac{i_{FC}}{A}\right)+0.062\left(\frac{T}{303}\right)^2\left(\frac{i_{FC}}{A}\right)^{2.5}]}{\left[\lambda-0.634-3\left(\frac{i_{FC}}{A}\right)\right]\exp[4.18\left(\frac{T-303}{T}\right)]} \quad (12)$$

where the term 181.6/(λ -0.634) is the resistance coefficient at no current and with 30°C of temperature. The exponential term in the denominator is the temperature correction factor when the cell is not at 30°C. The parameter λ is the adjustable parameter with the value ranging from 14 to 23. λ is the water content of proton exchange membrane.

3.2.3 Concentration Voltage Drop

The V_{con} is voltage drop resulting from reduction of concentration of reactant gases i.e. mass transport of oxygen and hydrogen. It can be described as

$$V_{con} = -Bln\left(1 - \frac{J}{J_{max}}\right) \quad (13)$$

For this voltage drop, maximum current density J_{max} is required. Typical values of J_{max} are in the range of 500-1500 mA/cm^2. B is the parametric coefficient which depends on the cell.

3.3 Power and Stack Voltage

The stack voltage can be calculated as

$$V_{st} = V_{FC}.N \quad (14)$$

where V_{st} is the stack voltage and N is the number of fuel cells used.

The power generated by a fuel cell stack can be represented as

$$P = V_{st}.i_{FC} \quad (15)$$

The current density of the cell J can be defined as

$$J = \frac{i_{FC}}{A} \quad (16)$$

4. RESULTS AND DISCUSSION

In this section, an analysis of the performance of the fuel cell is done for different operating conditions. In this paper work is done with variation in operating temperature, pressure. In this paper the analysis is also done taking active cell area into consideration as it also contributes to the performance of the cell. It also influences the efficiency of the fuel cell.

4.1 Effect of Temperature

In this paper, the temperature is varied from 323K to 363K and the fuel cell polarization curve is shown in Fig-2. The fuel cell polarization curve is subjected to different operating temperature which shows that the fuel cell performance improved with increase in temperature. From the figure, it is seen that an increase in temperature increases the voltage at the same current density and a decrease in temperature results in decrease of voltage at same current density. This indicates a significant effect on the performance of the fuel cell. Thus, the operating temperature is an important factor that affects the performance.

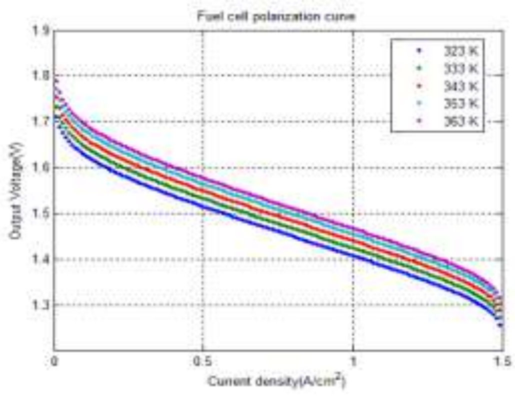

Fig-2: Effect of temperature changes on fuel cell performance

4.2 Effect of Fuel Pressure

Fuel pressure is another parameter that can have an effect on the fuel cell performance. This effect can be evaluated by varying the fuel pressure from 1 atm to 3 atm and the polarization curve is shown in Fig-3. It can be noted that an increase in the pressure increases the cell potential at the same current density and an upward shift is seen in the curve.

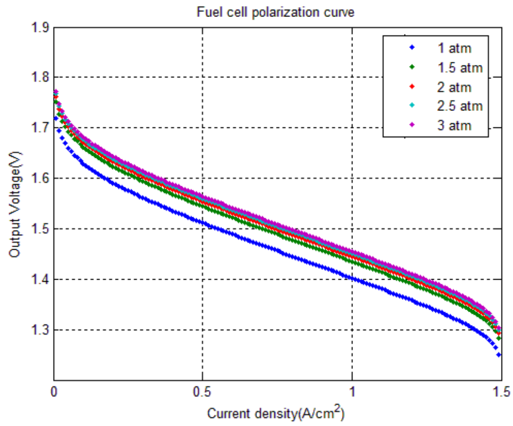

Fig-3: Effect of fuel pressure on fuel cell performance

4.3 Effect of Air Pressure

The effect of air pressure on the performance of the fuel cell is evaluated. The air pressure is varied from 0.6 atm to 1.4 atm and the result is illustrated in Fig-4. An upward shift of the curve can be seen with varying air pressure.

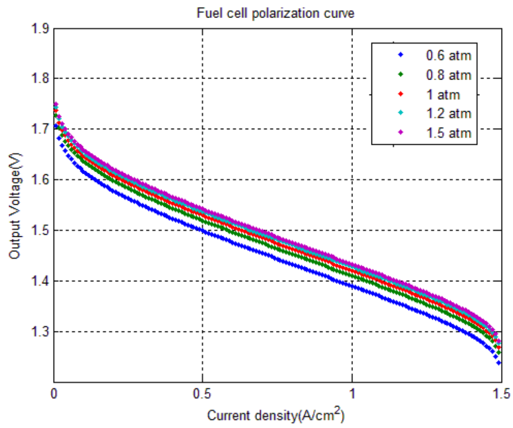

Fig-4: Effect of air pressure on fuel cell performance

4.4 Effect of Cell Active Area

Area is another important operating parameter that can affect the fuel cell performance. The performance of the fuel cell is studied under different cell active area ant the result is shown in Fig-5. The area is varied from 50 cm^2 to 100 cm^2. From the result, an increase in area results in a decrease in the voltage at the same current density.

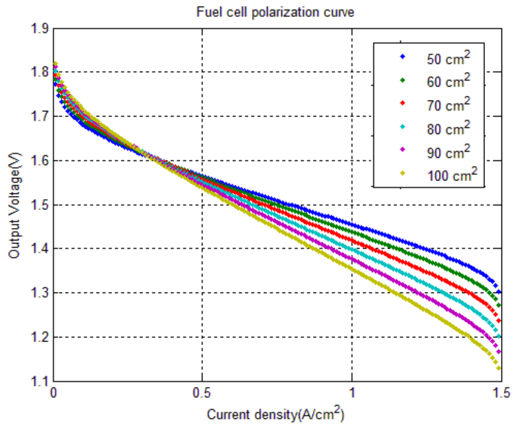

Fig-5: Effect of active area on fuel cell performance

4.5 Simulation Result

A fuel cell model is being created using the MATLAB/SIMULINK platform. The simulation of the model gives the power generated by the fuel cell and the stack output voltage. Figure 6 shows the simulink model of fuel cell.

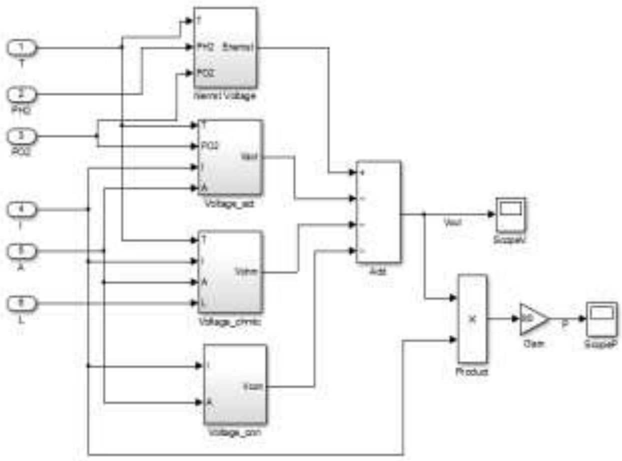

Fig-6: Simulink model of fuel cell

The maximum power output generated by the simulated fuel cell model is shown in Fig-7. The result shows a power output of approximately 8KW which is represented with respect to current density.

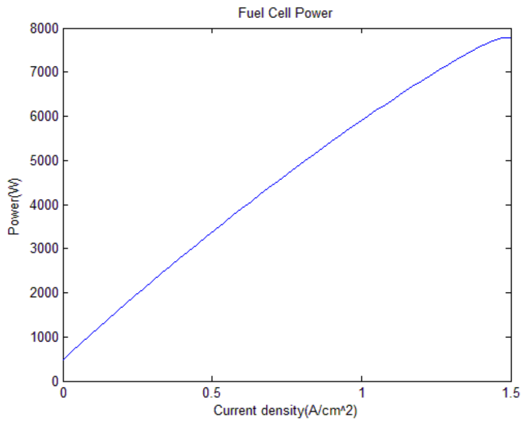

Fig-7: Plot of fuel cell power

The V-J characteristics is illustrated in Fig-8. The curve shows the output stack voltage of the simulated fuel cell model. The output voltage is required for the generation of the fuel cell power.

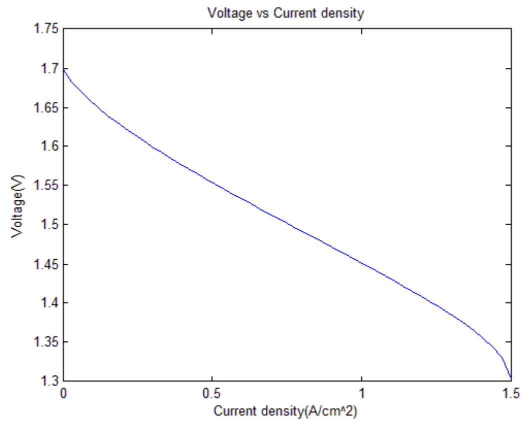

Fig-8: V-J characteristics of a fuel cell

Table-1: Parameter Values

R	8.314J/K.mol
F	96487C
T	80°C
T_{ref}	25°C
A	50 cm^2
l	50 μm
P_{H_2}	1.5 atm
P_{O_2}	1.5 atm
R_c	0.003Ω
ξ_1	-0.514
ξ_2	0.00286+0.0002ln(A)+4.3*10$^{(-5)}$ ln (CH_2)
ξ_3	0.41*10$^{(-4)}$
ξ_4	-0.92*10$^{(-4)}$
N	80

Table-1 shows the various parameters being used in the modelling of the fuel cell in Matlab/Simulink platform. This table has been chosen based on the above study done on performance analysis. So the given temperature, pressure and area are selected which provided a good result for power generation.

5. CONCLUSIONS

In this work, a fuel cell stack performance has been tested. Its performance based on different factors like temperature, pressure and active cell area has been investigated. It helps to provide a better fuel cell performance which can be used to produce more power with less input which in turn will increase its efficiency. The fuel stack was constructed with 80 cells. The work was carried out with hydrogen at anode and air (oxygen) at cathode side.

The simulation model constructed gives a better idea about the production of energy. The fuel cell stack was simulated at 80°C of operating temperature with 25°C as the reference temperature. The results showed that the stack has a maximum power of approximately 8 KW with 80 cells stack.

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