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Effect of Fuel Concentration on Power Generation in Bio-Fuel Cell

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***Abstract*—**Fuel cells are electrochemical devices that directly convert chemical energy to electrical energy. The fuel and oxidant do not mix with each other at any point in the fuel cell. Efficiency of bio-fuel cell with concentration of fuel is estimated. Various concentration of ethanol (100%, 50%, 25%) and H_2O (0%, 50%, 75%) were taken in the bio-fuel cell system and voltage generated were observed at different intervals of time.

***Keywords*—** Bio fuel cell; H_2O; ethanol; concentration.

I. INTRODUCTION

Thermodynamics is the study of the conversion of one form of energy into different forms of energy (in particular, mechanical, chemical, and electrical energy) and its relation to macroscopic variables such as temperature, pressure, and volume. In essence, thermodynamics studies the movement of energy and how energy instills movement. Historically, thermodynamics developed out of the need to increase the efficiency of early steam engines [1]. In fuel cells, thermodynamics is the key to understanding the principles of the conversion of chemical energy into electrical energy. It also sets the upper limit of what the fuel cell can do. In practice, fuel cells can never achieve thermodynamical voltage (also called open circuit or reversible voltage) – which for PEM fuel cells is 1.22V, and they are always operating below it, at about 0.7V depending on the current drawn from the cell [2].

The goal of the fuel cell is to extract the internal energy from a fuel and convert it into a more useful form of energy (electrical). Therefore it is necessary to know how much energy can be extracted from hydrogen. It all depends on the form in which we want to have this energy, either heat or work. The maximum heat energy that can be extracted from a fuel is given by the fuel‘s heat of combustion or, more generally, the enthalpy of reaction. Under constant pressure, the formula for enthalpy looks like this:

$$dH = TdS = dU + dW$$

where dH is Enthalpy of reaction, T is Temperature, dS is Entropy, dU is Internal energy, and dW is work. From the equation above, it can be seen that after accounting for the energy that goes to work, the rest of the internal energy difference is transformed into heat during the reaction. The internal energy change is mostly due to reconfiguration of chemical bonding, similar to that which takes place during the burning of hydrogen, when molecular bonding changes. This enthalpy change is called heat of combustion.

The work potential of the fuel, the amount of —usable‖ energy that can be recovered from it at constant pressure and temperature, is represented by Gibbs free energy.

$$G = H - TS$$

The equation above describes Gibbs free energy as enthalpy minus the energy connected with the entropy. In a fuel cell Gibbs free energy involves moving electrons round an external circuit. If there are no losses, or if the process is _reversible‘, then all the Gibbs free energy is converted into electrical energy (in practice, some is also released as heat.) It is then used to find the Open Circuit Voltage of the fuel cell [3-4].

In PEMFC two electrons pass round the external circuit for each water molecule produced and each molecule of hydrogen used. So, for one mole of hydrogen used, 2N electrons pass round the external circuit – where N is Avogadro‘s number. If −e is the charge on one electron, then the charge that flows is:

$$-Ne = -2F$$

where F being the Faraday constant, or the charge of one mole of electrons. If E is the voltage of the fuel cell, then the electrical work done moving this charge round the circuit is:

Electrical Work Done = Charge x Voltage $= -2FE$

If the system is reversible (or has no losses), then the electrical work that is done will be equal to the Gibbs free energy released $\Delta \bar{g}_f$ (molar Gibbs free energy).

$$\Delta \bar{g}_f = -2F.E$$

$$E = -\frac{\Delta \bar{g}_f}{2F}$$

This fundamental equation gives the electromotive force (EMF) or reversible open circuit voltage of the hydrogen fuel cell (Larminie and Dicks 2003). To account for reactant and product activity, a Nernst equation is used, which also includes pressure effects on reversible cell voltage, but does not involve temperature effects:

$$E = E^0 - \frac{RT}{2F}\ln\frac{\Pi a_{products}^{v_i}}{\Pi a_{reactants}^{v_i}}$$

E^0 in this equation is open circuit voltage and R is an ideal gas constant (8.314 J/mol·K). a represents the amount of products or reactants. For example, if pure oxygen is used the amount of this reactant will be 1. However, if we use air instead of pure oxygen, the amount will be 0.21, because there is 21% oxygen in the air [5-6]. v is the amount of moles of products/reactants used in the process – for instance if the reaction for PEM fuel cell looks like this:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

v for H2 would be 1, for O_2 – 0.5 and for water 1. The ideal efficiency is the amount of useful energy that can be obtained to the total amount of energy available. In the fuel cell that will be the amount of energy available to perform work (Gibbs free energy) to the heat of combustion of the fuel (enthalpy of the formation). Therefore the ideal, thermodynamic efficiency of the fuel cell is:

$$\varepsilon = \frac{\Delta \bar{g}}{\Delta \bar{h}}$$

At room pressure and temperature, the H2-O2 fuel cell has Δg = -237.3 kJ/mol and Δh = -286 kJ/mol, so the ideal efficiency of the fuel cell is 83%.

However, to calculate real efficiency one has to be aware of voltage and fuel utilization losses. Voltage efficiency of the fuel cell can be obtained from the ratio between the real operating voltage of the fuel cell V and open circuit voltage E. The fuel utilization efficiency accounts for the fuel that is not used to obtain electric power. It is the ratio of the amount of fuel used to generate current i/nF to the total amount of fuel delivered to the cell v_{fuel}.

$$\varepsilon_{real} = \left(\frac{\Delta \bar{g}}{\Delta \bar{h}}\right)\left(\frac{V}{E}\right)\left(\frac{i/nF}{v_{fuel}}\right)$$

Electrochemical reactions in the fuel cell occur on the surfaces and the involve transfer of electrons, therefore the rate of the reaction (generated current) is proportional to the reaction surface area [7]. To normalize and compare systems, current density (current per area unit - j) is used, instead of just current. To increase the speed of reaction, so the rate at which reactants are converted into products, a part of the fuel cell voltage is sacrificed to lower the activation barrier. This voltage is known as the activation overvoltage η_{act}. The activation overvoltage can be calculated from this equation:

$$\eta_{act} = -\frac{RT}{\alpha 2F}\ln j_0 + \frac{RT}{\alpha 2F}\ln j$$

Where α is a transfer coefficient (always between 0 and 1, usually 0.2 – 0.5), and j0 being exchange current density, which measures the equilibrium rate at which reactants and products are exchanged in the absence of activation overvoltage. Increasing j_0 minimizes activation overvoltage losses. Simplified version of this equation is called Tafel equation:

$$\eta_{act} = a + b\log j$$

In fuel cells, the voltage gradient is mainly responsible for the charge transport. It represents the loss of fuel cell performance, and it is called ohmic overvoltage. It generally obeys the Ohm‘s law of conduction:

$$V = iR$$

R, the fuel cell‘s resistance, is composed of the resistance of electrodes, electrolyte, interconnections etc., however the electrolyte resistance is the most significant one [8]. To calculate the fuel cell‘s resistance, we have to take into consideration the area of conductor A, its thickness L and conductivity σ. Therefore, the equation for R looks like this:

$$R = \frac{L}{\sigma A}$$

To be able to compare different size fuel cells, area-specific fuel cell resistance ASR is calculated, which uses the fact that resistance scales with area. This leads to the equation for fuel cell‘s ohmic overvoltage:

$$\eta_{ohmic} = jASR$$

One of the ways to decrease the effects of ohmic overvoltage is making the electrolytes in fuel cells as thin as possible. It is also critical to develop high-conductive electrodes and electrolyte material. In PEMFC, conductivity in Nafion is dominated by water content. A high amount of water leads to high conductivity.

To effectively generate current in the fuel cell, proper supply and removal of reactants and products is necessary. Mass transport governs the distribution of these compounds. If there are problems, such as reactant depletion or clogging of products, the fuel cell‘s performance is affected. Limitations in mass transport, especially in electrodes, lead to generation of a limiting current density jL, which corresponds to the situation where the reactants concentration drops to zero in the catalyst layer of the fuel cell. A drop in the amount of reactants affects the overall cell voltage and is called ―concentration loss‖. The voltage represented by these losses can be calculated with this equation:

$$\eta_{conc} = c\left(\frac{j_L}{j_L - j}\right)$$

where c is a constant that depends on the geometry and mass transport of the fuel cell. Concentration losses can be minimized by the careful design of a fuel cell‘s flow channels in bipolar plates. Parallel or serpentine designs (Figure 4.4) are preferred, because they provide a compromise between pressure drop, which is required to drive gas through the channels, and water removal capability, which is a big issue in a PEMFC [9-10].

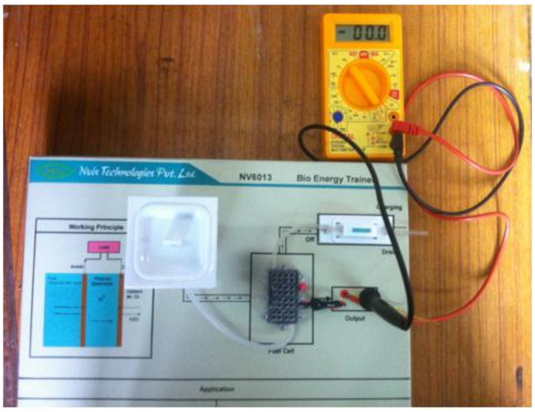

Fig. 1. Bio fuel cell system.

II. EXPERIMENT

The investigation were carried out on bio-fuel i.e. ethanol utilizing PEM fuel cell for electricity generation. The experimental set up is shown in Fig. 4.6. Electricity engendered from renewable energy sources could be acclimated to make hydrogen by an electrolyser from bio-fuel then hydrogen recombined with oxygen or dihydrogen monoxide in a fuel cell to engender electricity and then engendered electricity from bio-fuel cell system applied to the load. Ethanol bio-fuel is commixed with dihydrogen monoxide and then that liquid is applied to the bio-fuel cell system. Chemical reaction takes place between the ethanol solution, dihydrogen monoxide, and oxygen. Various experiments were carried out with different concentration of ethanol and water.

III. RESULTS AND DISCUSSION

Investigations were carried out with different concentrations of ethanol and water in bio fuel cell. Three set of experiments were carried out having a mixture of ethanol and water. In first experiment a mixture of 100% of ethanol and 0% water was taken. Table I shows the output voltage obtained and different intervals of time.

TABLE I. Voltage at different interval for 100% ethanol.

S. No	Output Voltage (V)	Time (sec)
1	0.3	0
2	1.1	5
3	1.2	10
4	1.2	15
5	1.3	20
6	1.3	25
7	1.4	30
8	1.4	35
9	1.4	40
10	1.4	45
11	1.4	50
12	1.4	55

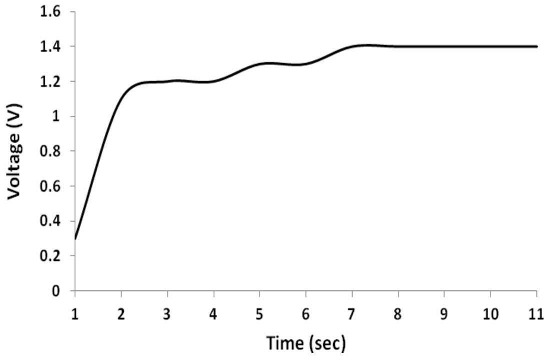

Fig. 5.10. Voltage generated at different interval of time for 100% ethanol.

Container filled by ethanol in beginning of experiment is 60ml and ethanol left in the container after the experiment is 55 ml. Therefore ethanol consumed is 5ml. The rate of flow of ethanol is 5ml/60s = 0.0833ml/s. In the second experiment equal concentration of ethanol and water are taken i.e. 50% of ethanol and 50% of water. Table II shows the output voltage at different intervals of time.

Container filled by ethanol in beginning of experiment is 60ml and ethanol left in the container after the experiment is 56 ml. Therefore ethanol consumed is 4ml. The rate of flow of ethanol is 4ml/60s = 0.0666 ml/s. In the third experiment lower concentration of ethanol and higher concentration of water are taken i.e. 25% of ethanol and 75% of water. Table III shows the output voltage at different intervals of time.

TABLE II. Voltage at different interval for 50% ethanol.

S. No	Output Voltage (V)	Time (sec)
1	0.6	0
2	0.7	5
3	0.7	10
4	0.7	15
5	0.7	20
6	0.8	25
7	0.8	30
8	0.8	35
9	0.8	40
10	0.8	45
11	0.8	50

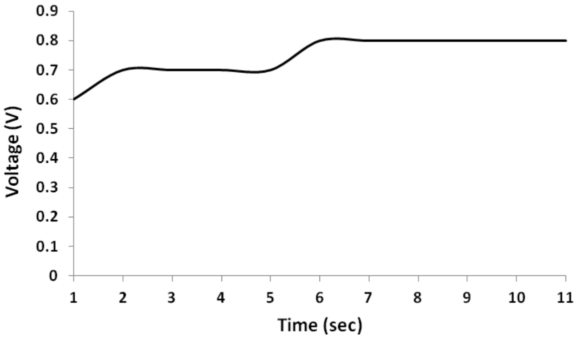

Fig. 5.11. Voltage generated at different interval of time for 50% ethanol.

TABLE III. Voltage at different interval for 25% ethanol.

S. No	Output Voltage (V)	Time (sec)
1	0.8	0
2	0.8	5
3	0.8	10
4	0.8	15
5	0.8	20
6	0.8	25
7	0.8	30
8	0.8	35
9	0.8	40
10	0.8	45
11	0.8	50

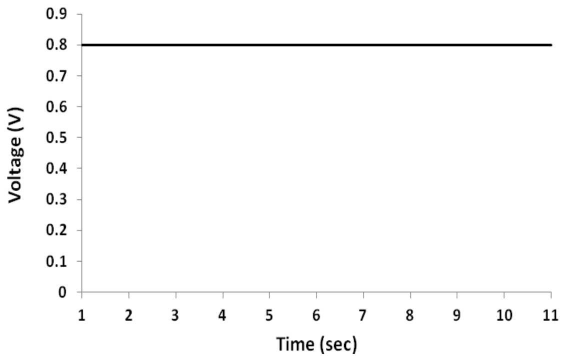

Fig. 5.12. Voltage generated at different interval of time for 25% ethanol.

Container filled by ethanol in beginning of experiment is 60ml and ethanol left in the container after the experiment is 56 ml. Therefore ethanol consumed is 4ml. The rate of flow ethanol is 4ml/60s = 0.0666 ml/s.

IV. CONCLUSION

In the research work investigations are carried out to estimate the power generation using bio fuel cell. Different concentration of water and ethanol were used as fuel. For 100% of ethanol voltage increases linearly and saturates at 1.4V. In case of 50% of ethanol, the saturation voltage is 0.8V. In the third experiment with 25% of ethanol, constant output voltage of 0.8V is obtained.

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