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Characteristic Study of Bio-Membrane PEM Fuel Cell for Performance Upgrading

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Abstract

Polymer electrode membrane (PEM) fuel cell has been intensively investigated to improve its output power as a new alternative energy resource. One vital part of PEM fuel cell is its membrane and its critical role in power production of fuel cell. Specifically, the thermal, hydrodynamic and ionic properties of membrane form the core mechanisms of energy generation inside PEM fuel cell.

In this simulation study a new design for PEM fuel cell (PEMFC) membrane is suggested based on mechanical and rheological properties of biological cellular membrane using mathematical-computerized modeling approach for total PEM fuel cell that had been built exclusively for the present study.

By using biomembrane, the output power of the PEM fuel cell in increased by 33% for the effective range of current density (i.e, 0.4 to 1.2 A/cm2), while the electrical efficiency is improved by 13%- 20% for the same current density range. Furthermore, for the same hydrogen pressure the output power of biomembrane fuel cell exceeded the power of conventional one by 17% and its electrical efficiency has the same percentage of growth (i.e 17%).

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Keywords: PEM fuel cell; biomembrane; fuel cell performance; cell efficiency

1. Introduction

Proton Exchange Membrane, also known as Polymer Electrolyte Membrane, (PEM) fuel cell delivers high power density, which offers low weight, cost, and volume. The immobilized electrolyte membrane simplifies sealing in the production process, reduces corrosion, and provides longer cell and stack life.

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PEM fuel cells operate at low temperature, allowing for faster start-ups and immediate response to changes in the demand for power. The PEM fuel cell system is seen as the system of choice for vehicular power applications, but is also being developed for smaller scale stationary power.

The PEM fuel cell was invented at General Electric (GE) in the early 1960s, through the work of Thomas Grubb and Leonard Niedrach. Initially, sulfonated polystyrene membranes were used as the solid electrolytes, but these were soon replaced by Nafion® membranes in 1966. The Nafion membrane has proved to be superior in performance and durability, and it is still the most popular membrane in use today [1].
As interest in PEM fuel cell research and development has intensified, more and more universities and institutes all over the world are becoming involved. So far several key innovations - such as low platinum catalyst loading, novel membranes, and new bipolar plates - make the application of PEM fuel cell systems more or less realistic [2, 3].
PEM fuel cell has been studied by many researchers analytically and experimentally for cell performance improvements. Rajalakshmi N. et. al.[4] studied design and development of modular fuel cell stacks for various applications. Likewise, Sohn Y. et al.[5] studied operating characteristics of an air-cooling PEMFC for portable applications while Hwang J. and Hwang H.[6] performed parametric studies of a double-cell stack of PEMFC using Grifoil™ flow-filled plates.
Sridhar P. et al.,[7] studied humidification studies on PEM fuel cell performance and Mutupally et al.[8], investigated diffusion of water in the nafion 115 membrane. While Wang L. et al.[9], performed a parametric study of PEM fuel cell performance. Alshorman A.[10, 11] introduced full modelling analysis for PEM fuel cell under different operating conditions and design parameters.
Normally PEM fuel cell could be investigated for power enhancement, new design developments, materials and structure modifications or improve operating conditions. In this study, a new design considerations and structure have been considered to improve cell performance and enhance efficiency. This is mainly based on biomembrane of PEM fuel cell, such that the membrane has the same hydrodynamic and thermal properties of bio-cell. This includes the permeability, thermal conductivity and electrical characteristics.

2. Principles of PEM Fuel Cells

The conversion of chemical energy to electrical energy in a PEM fuel cell occurs through a direct electrochemical reaction. It takes place silently and cleanly without combustion. The key part of a PEM fuel cell, which is known as a membrane electrode assembly (MEA), consists of a polymer electrolyte in contact with an anode and a cathode on either side. To function, the membrane must conduct hydrogen ions (protons) and separate either gas to pass to the other side of the cell. A schematic representation of a PEM fuel cell is shown in Figure 1 [12, 13, 14].

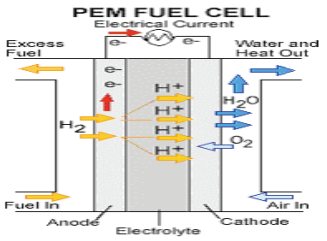

Figure 1: Diagram of PEM fuel cell principle [14]

3. Numerical and simulation methods

A mathematical analysis is used to address the main frame for PEM fuel cell performance and to build up the simulation mathematical and subsequent computerized models. Basically, this could be evaluated using sub-sequential dynamic values of main parameters such as membrane phase potential (ϕ), flow velocity ($\vec{v}$), ionic current density (i), cell voltage (V_{omic}), oxygen concentration (C_{O2}), hydraulic pressure (P_H), PEM fuel cell output power (P) and efficiency ($\wp$). The sub layers equations are investigated to introduce a differential equation for each of main parameters: ϕ , $\vec{v}$, i , V_{omic} , C_{O2}, P_H. Purposely, these equations should be solved simultaneously using the designed computerized model for the six unknown variables and then solve for P and $\wp$. However, the final forms

of differential equation for each region of PEM fuel cell are explained clearly in many previous studies [15, 16, 17, 18, 19, 20] but it is extensively covered through my previous studies [10, 11].

4. Model equations [15, 16, 17, 18]

Generally, fuel cell operation under isothermal conditions is described by mass, momentum, species, and charge conservation principles [4]. Purposely, the following equations are used in development of the mathematical model:

4.1 Nernst-Planck equation is used to determine species transport.

$$N_j = -q_j \ (F/R_uT)\, D_j C_j\, (d\phi/dz) - D_j \ (dC_i/dz) + C_j\vec{v} \quad (1)$$

Where j: is either a proton (Hydrogen ion, H^+), or water (H_2O), N_j: molar flux of species j (mol/ (cm^2-sec), q_j : charge on species j, F: Faraday's constant which is equal 96,484 (coulombs/equivalent), T: cell temperature (K), R_u: universal gas constant =8.314(Joule/(mol-K)), D_j: diffusion coefficient of species j (cm^2/sec), C_j: concentration of species j (mol/cm^3), ϕ: membrane phase potential (volts), $\vec{v}$: water velocity (cm/sec), and Z: Distance (cm).

4.2 Modified form of Schlogl's velocity equation.

The fluid motion is described using Schlogl's equation of motion, as shown in equation (2).

$$\vec{v} = (k_\phi/\mu)\, q_f\, C_f\, F)(d\phi/dz) - (k_p/\mu)(dp/dz) \quad (2)$$

Where K_ϕ: electro kinetic permeability(cm^2) , K_p: hydraulic permeability (cm^2) , q_f: charge of membrane fixed-charge-site (+1) , C_f: concentration of membrane fixed-charge-site (mol/cm^3) , μ: pour water viscosity (gram/(cm-sec)), P: hydraulic pressure (atm)

4.3 The ionic current density is calculated by the following equation:

$$i = -K_{eff} \ (d\phi/dz) + F \times C_f \times \vec{v} \times \varepsilon_{m,c} \quad (3)$$

Where K_{eff} : Effective membrane electrical conductivity (mho/cm), A mho per centimeter (mho/cm) is an older unit of electrical conductivity (also known as specific conductance). Mho is the reciprocal of ohm. Though siemens was introduced in the late 1970s, this unit can still be found in some old measurement instruments. 1 mho/cm = 100 S/m, $\varepsilon_{m,c}$: volume fraction of membrane in catalyst region,

5. The ohmic over potential is calculated by:

$$V_{ohmic} = i \times \ \eta z / k_{eff} \quad (4)$$

5.1 Cell Output Voltage

The fuel cell output voltage is calculated by the equation (5)

$$V_{out} = E_{nernst} - V_{ohmic} - V_{act} - V_{conc} \quad (5)$$

Where V_{out} : cell output voltage in volt.

5.2 Fuel Cell Power

The fuel cell power is calculated by:

$$Power = N_c \times V_{out} \times i \times A_c \quad (6)$$

Where Power in watt, N_c : number of cells, A_c: area of each cell, (cm^2).

6. Results and Discussion

The central results of investigation of simulation models for biomembrane PEM fuel cell are presented subsequently through figures (2) to (5) for wide ranges of operation conditions. The meaning of bio fuel cell (abbreviated with BC) is for that cell in which a biomembrane is used and it is differ from conventional cell (abbreviated with CC) by many parameter such as (Cell temperature(T), Membrane thickness(Z), Hydrogen Diffusion Coefficient(DH^+),Hydrogen concentration coefficient(CH^+) and Limiting Current Density(i_l)). The main operating and geometric parameters for the base case of biomembrane fuel cell are presented in table 1, while values for the membrane parameters and properties are given in table 2.

Table 1 Parameters for for Biomembrane PEM Fuel Cell

Parameter	Value & unit	Reference
Membrane thickness, Z	0.0006 cm	30
Cell temperature, T	10-40°C	12
Air-side pressure, P_a	1 atm	—
Hydrogen side pressure. PH2	0.5-5 atm	—
Number of Cells, N_c	1 cell	—
Area of Cell, A_c	100 cm^2	—

Table 2 Biomembrane Parameters and Properties.

Parameter	Value & unit	Reference
Hydrogen Diffusion Coefficient, DH^+	1×10^{-4} cm^2/sec	31,32
Hydrogen concentration coefficient, CH^+	1×10^{-3} mol/cm^3	31, 32
Exchange Current Density, i_o	1×10^{-7} A/cm^2	18
Limiting Current Density, i_l	1.411 A/cm^2	33

7. Ionic Current Density Effect

Figure 2 shows the effect of ionic current density on cell power and cell efficiency for both conventional and biomembrane PEM fuel cells. The current density varies within a range of [0-1.4 A/cm^2], It can be noted that ionic current density enhances cell power to reach its peak value of 100 W for bio-PEM fuel cell at current density of 1.2 A/cm^2 and 76 W for conventional PEM fuel cell at current density of 1.1 A/cm^2, and then it turns down beyond this limit to reach 80 and 50 W respectively. It is clear that biomembrane fuel cell has better performance than that of conventional one. This behavior is related to the cell voltage losses, which increases with current density and its effect will be dominant at current density higher that 1.0 A/cm^2, so it is responsible for power reduction after this current density margin. Furthermore, the results elucidate that the most favorable current density range for optimal cell power outcome is 0.7-1.4 A/cm^2 for both types of PEM fuel cell.

A single-phase analysis such as the present model and all models still provides a good first approximation of cell performance for current densities above 0.6 A/cm^2. This is true because the water distribution affects the electrochemical process and oxygen transport in the air cathode primarily in two ways. First, the presence of liquid water affects the water content in the membrane and thus slightly alters its ionic conductivity of the cell, but at high rate for biomembrane structure. More important, liquid water present in the gas diffusion cathode hampers oxygen transport to the catalyst layer. However, recent two-phase calculations indicated that there is only 5% of the liquid water saturation at current densities as high as 1.5 A/cm^2, making the effect of liquid water existence on the oxygen transport likely minimal. For these reasons, the single-phase analysis is still applied to predict cell performance for current densities greater than 0.6 A/cm^2 in the following without consideration given to the water distribution [16, 22, 23].

On the other hand cell electrical efficiency of bio-fuel cell has its higher value at lower current density and it is gradually decreases from 74% at 0.0 A/cm^2 to 67% at 0.81 A/cm^2 current density. However this efficiency range is higher that of conventional PEM fuel cell by (7%-18%) for the same current density range as shown in figure 3. This performance may be explained by the direct relation of cell voltage losses to current density. So the increase of current density will enhance voltage losses and this causes electrical efficiency to be less, also it indicates that biomembrane may reduce the tendency for voltage loss of the PEM fuel cell. In principle, this suggests that the PEM fuel cell must be operated at low current density to have sensible cell electrical efficiency.
The ohmic over potential is a combined result of the resistance to proton transfer across the membrane and the resistance to the electron flow through the electrode materials and the interconnections. The membrane conductivity depends on the membrane thickness as well as the membrane's hydration index. Since the membrane is assumed to be fully hydrated, the cell potential increased as the membrane thickness decreased, and this highlights the suitability of biomembrane for activation of PEM fuel cell performance. Reducing the membrane thickness results in improved performance. However, the membrane must be thick enough to remain mechanically sound during cell assembly and operation. Fuel crossover from the anode to the cathode is a potential problem if the membrane thickness is too small [24, 25, 26, 27].

From curve (Figure 2 and 3) the bio-PEM fuel cell gives power (and efficiency) more than the conventional cell; And that because the thickness of the bio-cell is smaller than in conventional cell thus the ohmic losses in bio cell is less than in conventional cell, hydrogen concentration coefficient value, hydrogen diffusion coefficient value, and temperature differ in conventional cell and bio-cell.

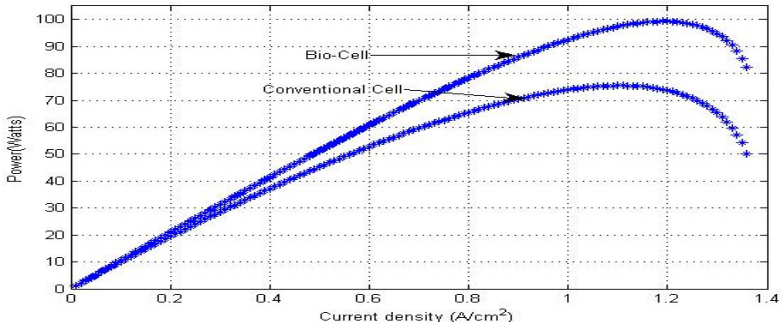

Figure 2 Current density effects on power (BC and CC)

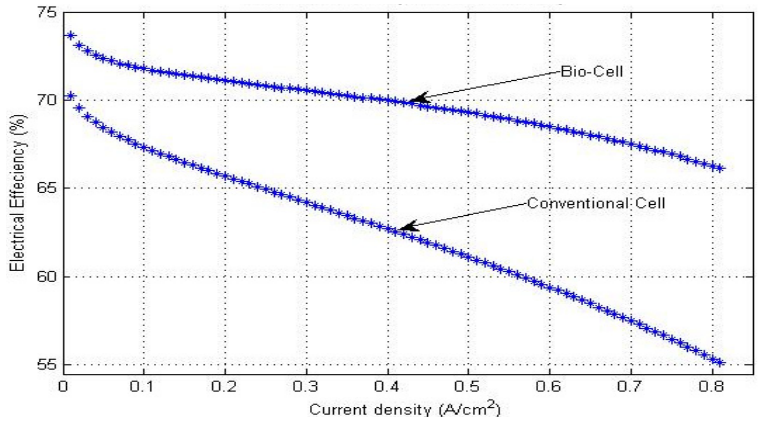

Figure 3 Current density effects on efficiency (BC and CC)

8. Hydrogen Pressure Effect

Hydrogen could be considered as the fuel of PEM fuel cell, and its partial pressure has a key role in fuel cell performance. Its value enhances Nernst voltage, and as a result the total output voltage and cell power will be favorably affected. Accordingly, the effect of hydrogen pressure on cell power has been tested over a range of (0.5-5.0) atm for both biomembrane PEM fuel cell and conventional one. Generally, the long-term operating pressure of hydrogen in PEM fuel cell will affect the cell structure, geometry and materials of components. Also the membrane material, thickness and permeability are strongly related to hydrogen pressure as the membrane is the intermediate stage of the fuel cell.

The effects of hydrogen pressure on cell power and efficiency are demonstrated through figures 4 and 5. The hydrogen pressure enhances both cell power and electrical efficiency at different rates. However, cell power gets its sharp increase within a pressure range of (0.5-2.5) atm, then it has slightly gradual raise after 3.0 atm as presented in figure 4. It could be noted that bio PEM fuel cell gives higher power rate of about 15% and higher cell efficiency of 17% than that of conventional one for the same hydrogen pressure range.

These findings suggest that change of hydrogen pressure has less considerable influence on cell electrical efficiency in comparison to that on cell power.

A comprehensive analysis for hydrogen pressure in utilization of energy is reported by Grégoire Padró , C. E., and Lau. F. [28]**.** They investigated hydrogen generation, storage, handling, permeability and its industrial applications.

This significant enhancement of fuel cell performance by bio membrane over hydrogen pressure range is due to ionic and rheological properties of bio membrane and its active interactions to hydrogen. This membrane has hydrogen diffusion coefficient, D_{H+} of 1×10^{-4} cm ^{2}/sec and Hydrogen concentration coefficient, C_H of 1×10^{-3} mol/cm^3, that both are less than that of conventional membrane. And according to Nernst-Planck equation (i.e., eqn (1)) the lower the hydrogen diffusion and concentration coefficients the higher the flux of species through the membrane will be and consequently the current density and fuel cell outcome. More specific technical details are explained by Gross M. et al., [29].

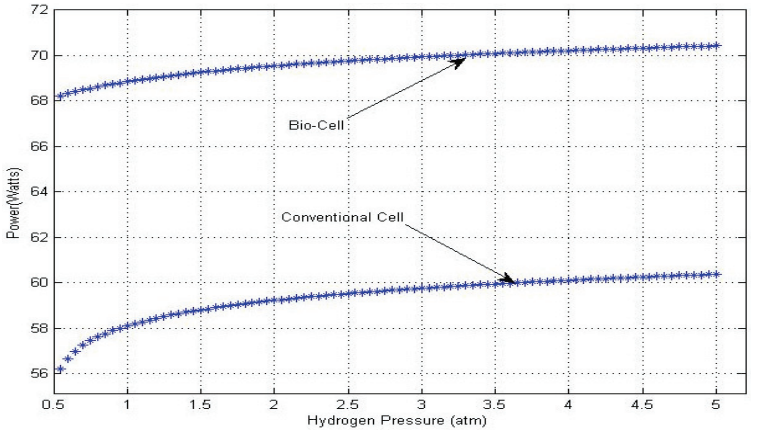

Figure 4 Hydrogen pressure effect on power (BC and CC)

Figures 4 and 5 elucidated that it is possible to get higher power output and electrical efficiency using bio PEM fuel cell than conventional one over the same hydrogen pressure range, but the range of increase is converse. So the power output of conventional fuel cell is increased from 56 W to 62 W (i.e., about 10%) while it was from 68 W to 71W (i.e., about 4%) for biomembrane one over the same range of hydrogen pressure. Also the conventional fuel cell efficiency was enhanced by 8% against 3% for biomembrane one.

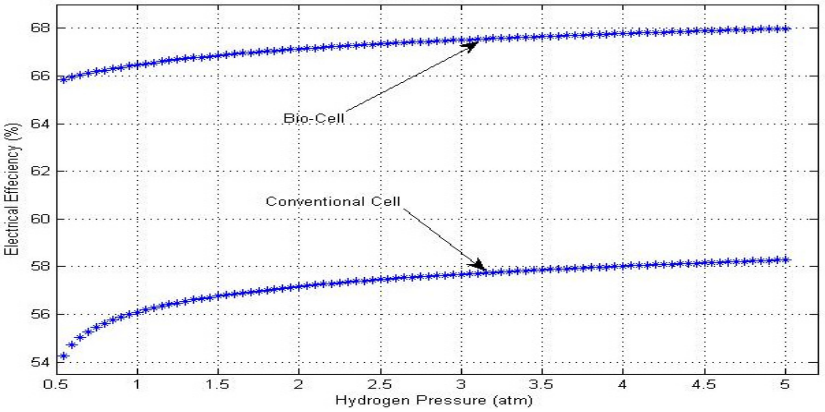

Figure 5 Hydrogen pressure effect on efficiency (BC and CC)

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