Hybrid power plant of the photovoltaic-fuel cell

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Abstract. The purpose of this research is to study the performance of hydrogen fuel cell to study different fuel flow rate and different concentration to obtain the optimum performance of the cell. First, design a hydrogen fuel cell model, second simulate cell performance toward hydrogen fuel flow rates of 6, 18, and 30 mL/min and fuel concentrations of 50 mol/m^3. Subsequently, we obtained the characteristics of voltage-electric current density and power density-electric current density per stack of fuel cell. The research of this hydrogen fuel cell obtained the power density optimum of 0.0471 mW/cm^2 at a cell current density of 0.135 mA/cm^2 and a cell voltage of 0.35 V. The greater the load the greater the time used by the battery for instant loads. The average time when the load is small is 10 W with a time of 240 hours and the fastest time when a large load is 400 watts with a time of 6 hours. Decreasing battery discharge time to the same load due to the completion of power losses in each device or circuit that produces the power generated by the battery does not reach the maximum load.

1. Introduction

Fuel cells or more commonly known as "fuel cells" are new and renewable energy sources that are being researched and are becoming research topics in the last decade. Fuel cells are an environmentally friendly energy source because they do not cause pollutants and can be used renewably, have a wider application range, are easy to control, have no interference if integrated into the system, and can be combined as a microscale hybrid power generation system [1-3]. Research on proton exchange membrane-type fuel cells (PEMFC: Proton Exchange Membrane Fuel Cells) both using gases and liquid solutions as fuels has been widely carried out [4,5]. This shows that the potential of fuel cell-based power plants has big opportunities and wide applications in various fields, such as medicine, computers, telecommunications, and so on. But research related to micro-scale fuel cells is still very little and has not been done much in Indonesia. The technology of proton-type micro-scale cell fuel membrane proton exchange has been widely patented and researched. However, the average of these patents and research only examines the structure and electrode design and PEMFC performance at certain temperature variations [6-8]. While the parameters of volumetric flow rates, fuel concentrations, generated voltage-currents and numerical simulation models of species transfer and momentum transfer in fuel cells, are rarely studied [9,10]. For this reason, it is necessary to develop a numerical simulation model of these parameters in proton-type membrane fuel cells (PEMFC), with optimum performance characteristics. This research is focused on proton-type membrane cell type (PEMFC) fuel cells oriented to optimum performance, both model design and numerical simulation prior to the micro-scale PEMFC fabrication process, so that PEMFC models will be produced whose components are easily obtained at low cost and easily duplicated.

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2. Research methods

2.1. Design of PEM fuel cell model

This study carried out through two stages, namely the design of Proton Exchanger Membrane Fuel Cells and numerical simulations of fuel cells. The Proton Exchange Membrane Fuel Cell (PEMFC) Fuel Cell Model has a channel dimensions of 200mm x 10mm x 10mm.

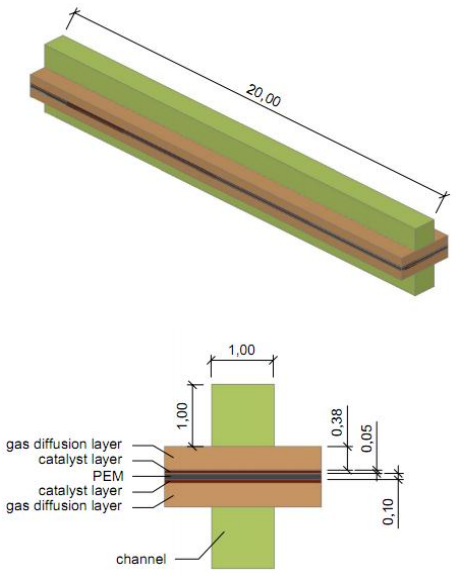

Figure 1. Design of PEM fuel cell stack.

Both the anode and cathode electrodes have dimensions of 2.75 mm x 200 mm, with the distance between the electrodes being 0.1 mm. The two electrodes are placed on the bottom side of the microchannel. Figure 1 illustrates the PEMFC model which consists of seven main parts namely the anode-side micro fuel channel, the gas diffusion porous layer on the anode side, the catalyst layer on the anode side, the polymer thin membrane layer, the cathode-side catalyst layer, the cathode-side porous gas diffusion layer, and the cathode side fuel microchannel. Miniaturization of the fuel cell with the structure and design of the PEMFC unit stack is shown in Figure 1.

2.2. Numerical simulation of the fuel cells

Hydrogen fuel cells enter through the anode inlet side, while oxygen will flow into the microchannel on the cathode inlet channel side. Both gases will react electrochemically to the surface of the anode and cathode catalyst layer. The hydrogen gas ions (H +) will flow through the membrane and move from the anode side to the cathode side, while electrons (e-) will move to flow from the cathode side to the anode side. Electrons from the negative anode pole will flow through the bipolar collector plate through the external circuit to the positive pole of the cathode to generate an electrical load. Fuel cell stack models for micro-scale PEMFCs can be seen in Figure 2 and Figure 3.

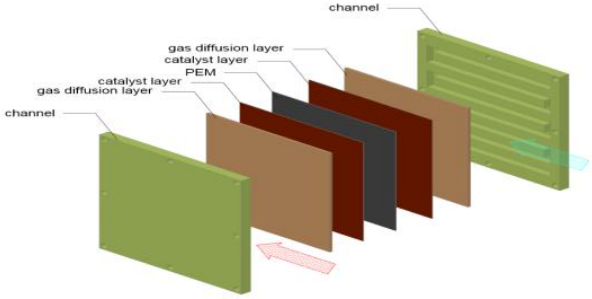

Figure 2. Single cell stack model for micro scale PEMFC.

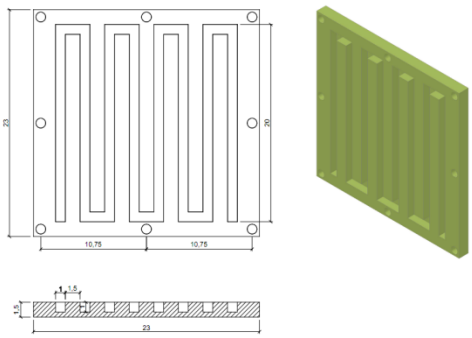

Figure 3. Microchannel serpentine model for micro scale PEMFC.

Numerical simulation based on the 3-dimensional element finite method is implemented in COMSOL Multiphysics 5.1. The 3-dimensional model of the fuel cell is designed with COMSOL to solve the fluid transport phenomenon that is the equation of the flow of gas fluid distribution in the micro channel, the equation of fluid flow passing through the porous media [9], the diffusion and convection equation, the electric charge equation according to the electrochemical reaction that occurs on the surface of porous electrodes and catalysts. This numerical simulation will discuss the performance of proton exchange membrane fuel cells related to the current and voltage polarization curves generated, including overpotential on the electrodes, distribution of fuel and oxidant concentrations, and distribution of fluid velocity on micro channels. In addition, the performance of numerical simulation models is compared with experimental data as a reference to validate that the performance of models is appropriate and accurate.

3. Results and discussions

3.1. Fuel cells calculation analysis

This study to obtain optimal fuel cell performance by varying 3 pieces of fuel flow rates namely 6, 18, and 30 mL/min as shown in Figure 4, Figure 5, and Figure 6. Characteristics of fuel cell voltage and Electric current can be calculated using equation [3,6]:

$$E_{cell} = E_{OCV} - (\eta_{a,a} + \eta_{a,c}) - \eta_r \quad (1)$$

Where E_{ocv} is the open-circuit voltage in the experiment that can be obtained from the characteristic curve IV according to the load flow rate of a given fuel, it can be seen in Figures 4, 5, and 6. The fuel flow rate greatly affects the performance of the fuel cell, this is related with the electro-oxidation reaction rate of the fuel on the anode side and the electro-reduction reaction of the oxygen rate on the cathode side, as given in equation [6,11,12]:

$$S_i = \left(\frac{i_0}{n_i F}\right)\left(\frac{c_i}{c_{i,ref}}\right)^{\beta_i}\left[\exp\left(\frac{\alpha_a F\eta}{RT}\right) - \exp\left(-\frac{\alpha_c F\eta}{RT}\right)\right] \quad (2)$$

Where i_0 is the change in current density in the fuel cell (exchange current density) at the concentration of the fuel $c_{i,ref}$, the order of reaction to the species "i" as a reference step for the charge transfer in the cells α_a and α_c is the charge transfer coefficient at the anode and cathode, η is over-voltage, T is the operating temperature of the cell, F is the Faraday constant, and R is the universal gas constants. Oxygen supply from the surrounding air penetrates through the gas diffusion electrode (GDE) before reaching the catalyst layer at the cathode. Through the boundary conditions approach and entering values into equations (1) and equation (2), the oxygen concentration that passes through the GDE can be determined.

In the fuel cell electrochemical reaction, the electrochemical reaction always takes place on the upper surface side of the electrode, in this case the catalyst layer on the anode side and the catalyst layer on the cathode side. As it is known that, the anode and cathode electrodes are both made of a porous carbon

layer which is coated with a thin layer on the side of the catalyst particles. This catalyst layer is tested as a boundary condition, which corresponds to the electrochemical reaction that occurs on the surface side of this boundary condition (catalyst layer). So that from the electrochemical reaction on the surface of the catalyst layer seen at the concentration of species as known as the source (source term), the term source term in the species conservation equation is [6,7],

$$S_i = \nabla \cdot \left(-D_i \nabla c_i + c_i \vec{u} \right) \tag{3}$$

Here S_i is the rate of consumption of "i" species per cubic meter is caused by electochemical reactions along the surface of the catalyst layer on the anode and cathode sides. D_i is the diffusion coefficient of the species "i" for hydrogen gas on the anode side and oxygen on the cathode side according to the porous media at the electrode. Species diffusion coefficient values for the reaction at the anode and cathode are shown as the diffusivity of hydrogen gas and oxygen diffusivity which passes through the gas diffusion electrode (GDE) made of carbon layers.

On the surface along the catalyst layer, only the normal flux of the electrode and fuel surface influences and contributes to the fuel cell's output power as written in equation below [6,7],

$$\vec{n} \cdot \nabla \cdot \left(-D_{ij} \nabla c_i + c_i \vec{u} \right) = S_i \tag{4}$$

The porous structure of the anode and cathode electrodes has an effect on the binary diffusion coefficient used in the electrode as a porous medium to be corrected for electrode porosity (ε) and turtuosity or surface roughness at the electrode (τ) as follows [6,7],

$$D_{ij}^{eff} = D_{ij} \frac{\varepsilon}{\tau} \tag{5}$$

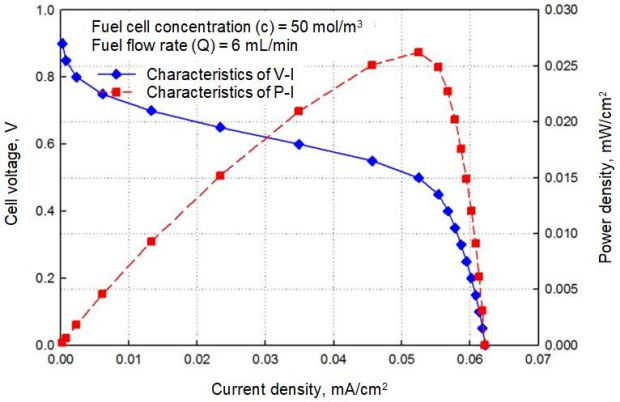

Figure 4. Characteristics of PEMFC with a hydrogen fuel concentration of 50 mol/m^3 and a fuel flow rate of 6 mL/min.

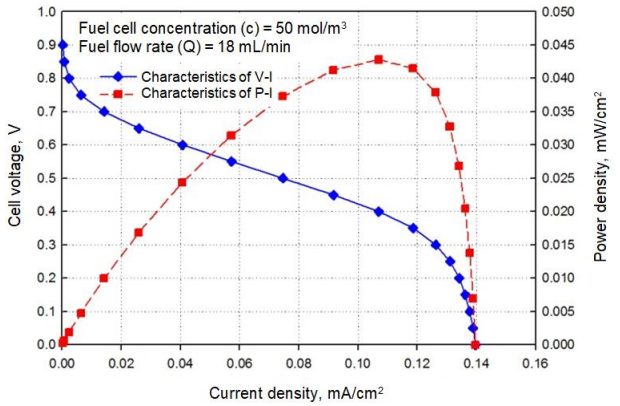

Figure 5. Characteristics of PEMFC with a 50 mL/m^3 hydrogen concentration and a fuel flow rate of 18 mL/min.

Performance simulation of PEMFC models at different fuel flow rates of 6 mL/min, 18 mL/min, and 30 mL/min at 50 mol/m^3 hydrogen fuel concentration, as shown in Figure 4, Figure 5, and Figure 6. Simulation results show that the fuel flow rate at the anode side channel which is getting bigger, will increase the accumulation of electric current produced by the fuel cell. Likewise, there will be an increase in the power of the fuel cell produced. Therefore, one way to obtain the optimum performance of the fuel cell is by knowing the conditions of the fuel flow rate parameters. Although many other parameters that will affect the performance of the fuel cell, among others is to vary the fuel concentration, membrane conductivity value, membrane and electrode permeability value, flow velocity on the inlet channel side, catalyst loading, temperature, and electrolyte concentration.

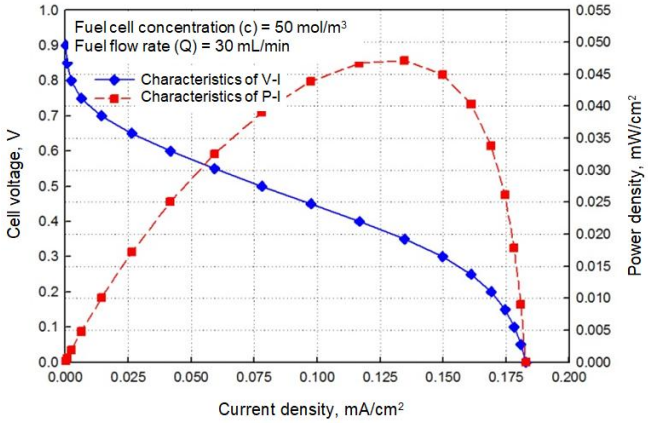

Figure 6. Characteristics of PEMFC with 50 mol/m^3 Hydrogen concentration and 30 mL/min fuel flow rate

3.2. Analysis ofhybrid power PV-fuel cells

3.2.1. Analysis on the battery charging process. The test results show the battery charging process. The battery charging process is influenced by the amount of current used for charging and the battery specifications. In this charging process, the battery uses two car batteries that are installed in series with a total specification of 24V 100Ah.

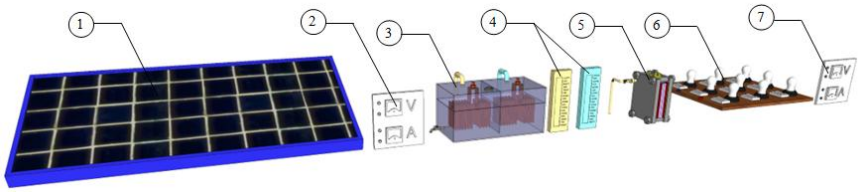

Figure 7. Design of hybrid PV-fuel cell models: 1. power sources (solar cells); 2. voltmeter & ampere meter input; 3. electrolyzer box; 4. flowmeter; 5. fuel cell; 6. load; 7. voltmeter & ampere meter output.

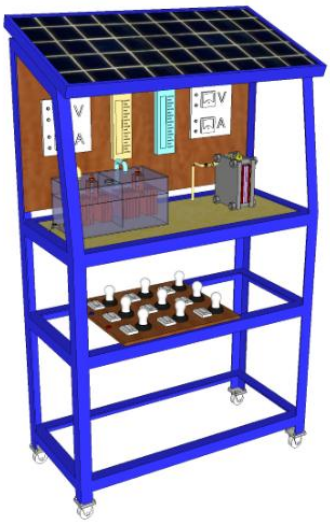

Figure 8. The Hybrid PV-Fuel cell power generation model.

This test is carried out during cloudy weather and starts at 09.00-14.00 with a time scale of 30 minutes. In this test the weather is very influential on the charging system, especially for solar power plants.

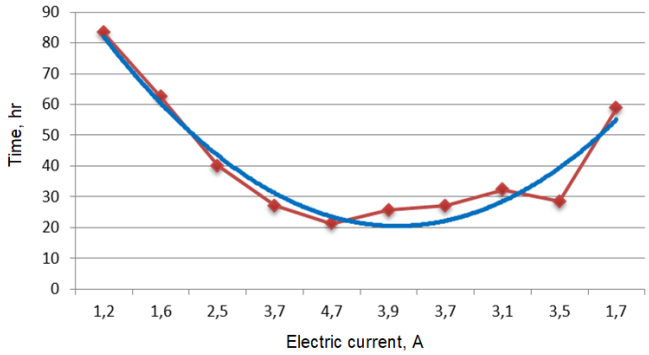

Figure 9. The relationship between current and battery charging process time.

Figure 9 shows that the amount of current is very influential on the charging time. The greater the current produced, the smaller the time spent by the battery for charging. From the calculation of the battery charging process above the fastest time for charging is 21.28 hours for a total current of 4.7 amperes at 11:30 while the longest time for battery charging is 83.34 hours for currents of 1.2 amperes occurring at 09.30.

3.2.2. Analysis on the battery discharging process. Test results on the battery discharging process are shown in Figure 8. Similar to the charging process, in this discharging process the battery uses two car batteries that are installed in series with a total specification of 24V 100Ah and are fully charged. This test uses a light bulb load with a varied power and on a time scale of 10 minutes.

3.2.3. Actual battery discharge analysis. The results of the calculation analysis for the length of time the battery is turned on during the actual battery discharge process are shown in the Figure below.

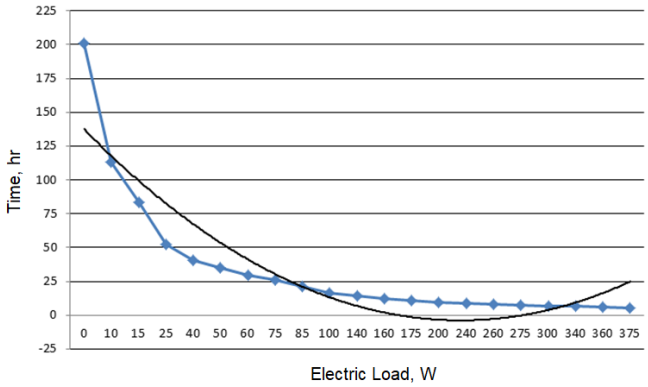

Figure 10. The relationship between load and time of use in the actual battery discharge process.

Figure 10 shows the size of the load is very influential on the discharge time. The greater the load used, the smaller the time used by the battery to turn on the load. From the actual calculation above the highest time taken when a small load of 10 watts with a time of 200.803 hours and vice versa the fastest time taken when a large load of 400 watts with a time of 5.68 hours.

3.3. Theoretical battery discharge analysis

The results of the analysis of calculations for the length of time to start using the battery theoretically in the process of emptying the battery.

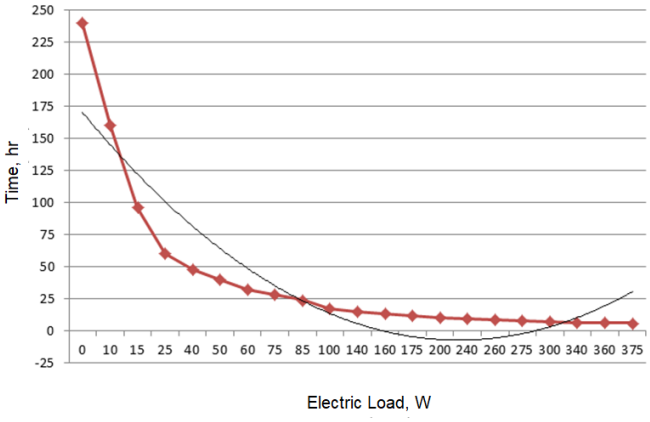

Figure 11. The theoretical relationship between load and time of use in the battery discharge process.

Figure 11 shows the size of the load is very influential on the discharge time. The greater the load used, the smaller the time used by the battery to turn on the load. From the actual calculation above the highest time taken when a small load is 10 watts with 240 hours and vice versa the fastest time taken when a large load is 400 watts with a time of 6 hours.

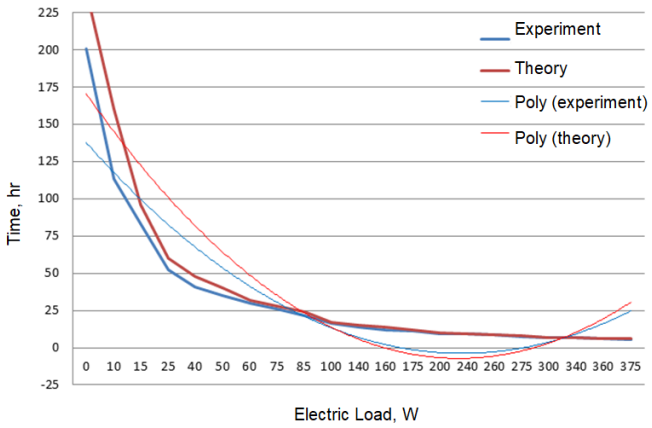

Figure 12. The relationship between the load and time of use in the actual battery discharge process and theoretically.

Figure 12 shows the reduction in battery discharge time for the same load. This is because due to the power losses on each equipment and circuit that results in the power generated by the battery not reaching the maximum load.

4. Conclusion

The results showed that the open circuit voltage in the fuel cell increased slightly with increasing fuel flow rate in the reactants in the micro channel. Open circuit voltage can vary under conditions of varying fuel flow rate which is around 0.35 V. Besides that the surface conditions of the electrodes will affect the change in current. Low open circuit voltage will trigger the formation of air bubbles in the fuel lines. The fuel cell micro channel has a width of 1.0 mm, a depth of 1.0 mm, and a length of 20 mm. The thickness of the MEA (Membrane Electrode Assembly) is 0.53 mm, including a 0.38 mm thick gas diffusion layer, a 0.05 mm thick catalyst layer and a 0.10 mm thick membrane layer. The maximum power density will gradually increase as Reynold's value increases. The maximum power density is achieved at 0.026, 0.042, and 0.047 mW/cm^2, for fuel cells at a flow rate of 6, 18, and 30 mL/min at a fuel concentration of 50 mol/m^3.

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