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An Investigation of GDL Porosity on PEM Fuel Cell Performance

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One of the design parameters of fuel cell is GDL (gas diffusion layer) porosity which helps to remove the water produced and accumulated in the catalyst layers toward the flow channels. In this study, a three-dimensional, isothermal model of a proton exchange membrane (PEM) fuel cell with a straight flow field channel has been developed to investigate the influence of the GDL parameters on performance of PEM fuel cells. The effects of the GDL porosity ranging from 0.3 to 0.6 at different gas channel width were examined. The cell performance is evaluated by the cell voltage–current density curves. The results showed that both the porosity of the GDL and flow field channel affect the fuel cell performance significantly. With porosity in the range 0.3-0.6, a better cell performance can be obtained with higher porosity of gas diffusion layer. And also it was noticed that increasing the channel width while the cell width remains constant decreases the current density.

1. Introduction

Fuel cell is an electrochemical device that continuously changes the chemical energy of a fuel (hydrogen) and oxidant (oxygen or air) directly to electrical energy and heat, without combustion. The proton exchange membrane fuel cell (PEMFC) is considered to be a promising power source, especially for transportation and stationary cogeneration applications due to its high efficiency, low operating temperature, high power density, low emission and low noise. A PEMFC is composed of the catalyst layers, membrane, gas diffusion layers and bipolar plate.

Gas diffusion layer (GDL) is one of the main components in PEMFC. The most important role of GDL is to conduct electrons to and from the catalyst layers. The performance of a PEMFC is affected by many factors such as temperature, pressure, relative humidity, mass flow rate of feed gases, channel geometries in current collector plate and the characteristics of the membrane, catalyst layer, and gas diffusion layer. Various properties of the GDL such as permeability, porosity, tortuosity, and the hydrophobic treatment can affect the fuel cell performance. In literature, several modelling and experimental work has been investigated in order to understand the effect of GDL properties and some of these parameters to the fuel cell performance.

It was observed that the cathode GDL porosity has the strongest effect on the cell performance following the cathode catalyst layer (CL) porosity, while the anode GDL and CL porosities have negligible effect (Wang et al., 2012). The optimization of parameters of cathode GDL and CL is more important in improving cell performance than that of anode GDL and CL. A detailed steady-state; isothermal, two-dimensional model of a PEMFC a finite element method was used to solve this multi-component transport model in membrane (Guvenlioglu et al., 2005). The model-predicted fuel cell performance curves were compared with published experimental results. The effects of channel width and bipolar plate shoulder dimensions, porosity, and the relative humidity of the inlet streams on the fuel cell performance were evaluated. It was found that smaller width channels and bipolar plate shoulders were required for high current density operations.

The designs of flow channels can significantly affect the performance of fuel cells under the same other operation conditions from experimental tests and numerical calculations. (Liu et al., 2013). Minimized total width of flow channels and ribs as well as the rib ratio can significantly improve the fuel cell performance.

A 3-D multiphase model has been developed to investigate the effect of the anisotropic thermal conductivity of the GDL on the performance of PEM fuel cells (Alhazmi et al., 2013). It has been found that the maximum

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temperature in the PEM fuel cell decreases when the thermal conductivity increases under the operating conditions investigated.
The mass transport for both the fuel and air increases as the porosity of the GDL ranging from 0.3 to 0.6 increases (Jang et al., 2006). Therefore, more reactant gases transfer into the catalyst layer, which in turn, leads to more chemical reaction and more reactant gases consumed. This results in a better performance for the fuel cell with a higher GDL porosity within the range of 0.3–0.6.

2. PEM fuel cell principles

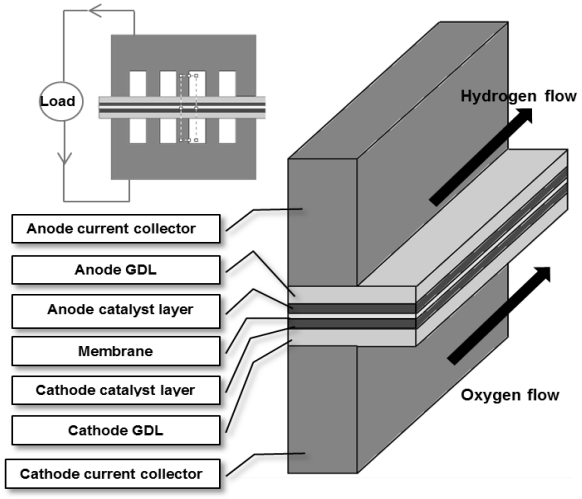

Figure 1: Schematic of the PEM fuel cell

A PEMFC (Figure1) is composed of the catalyst layers, membrane, gas diffusion layers and bipolar plate. Air or oxygen gas enters the cathode channel, and hydrogen gas enters the anode channel. The hydrogen diffuses through the anode diffusion layer towards the catalyst layer, where each hydrogen molecule splits up into two hydrogen protons and two electrons on catalyst surface according to:

$$2H_2 \rightarrow 4H^+ + 4 \quad (1)$$

The protons migrate through the membrane and the electrons travel through the conductive diffusion layer and an external circuit where they produce electric work. On the cathode side the oxygen diffuses through the diffusion layer, splits up at the catalyst layer surface and reacts with the protons and the electrons to form water:

$$H^+ + 4e + O_2 \rightarrow 2H_2O \quad (2)$$

Eq (1) is slightly endothermic, and Eq (2) is heavily exothermic, so that overall heat is created. From above it can be seen that the overall reaction in a PEM fuel cell can be written as:

$$2H_2 + O_2 \rightarrow 2H_2O \quad (3)$$

Based on its physical dimensions, a single cell produces a total amount of current, which is related to the geometrical cell area by the current density of the cell in [A/m²]. The cell current density is related to the cell voltage via the polarization curve, and the product of the current density and the cell voltage gives the power density in [W/m²] of a single cell. (Maher, 2007)

3. Model description

A complete single cell PEMFC (Figure 1) assembly divided into cathode current collector plate, gas diffusion layers, catalyst layers and anode current collector plate, gas diffusion layers , catalyst layers and membrane were constructed in Gambit2.4.6 and proper boundary conditions were introduced. The computational full model of a single fuel cell (Figure 2a) would require very large computing resources and long times. So the model is therefore limited to one straight flow channel with the active layer (Figure 2b). Boundary conditions are set as follows: constant mass flow rate at the channel inlet and constant pressure condition at the channel outlet.

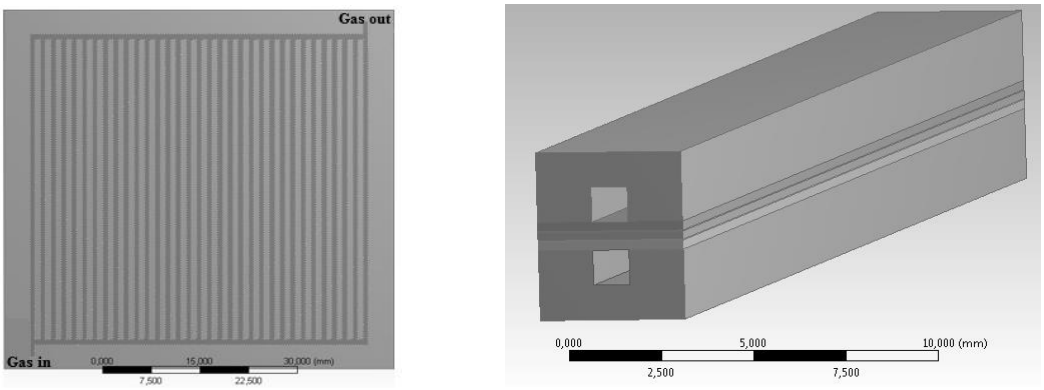

Figure 2: a)Current collector plate with straight channel, b) One straight flow channel of a PEMFC

3.1 Assumptions

The present model assumes ideal gas mixtures, steady-state conditions. The flow is laminar and system is isothermal. Electrodes, catalyst layer and membrane are isotropic and homogenous.

3.2 Governing equations

In the porous GDLs the Navier-Stokes equations have to be corrected for the porosity ε of the carbon fiber paper. Thus, the conservation equation for mass becomes:

$$\nabla\left(\rho_g \varepsilon_g u_g\right)=0 \tag{4}$$

whereas the momentum equation reduces to Darcy's law:

$$\varepsilon_g u_g=\frac{k_p}{\mu_g}p_g \tag{5}$$

where k_p denotes the hydraulic permeability. It was mentioned earlier that the liquid water pores are de-coupled from the gas pores, and Darcy's law is again used for liquid water transport:

$$\varepsilon_1 u_1=-\frac{k_p}{\mu_1}p_1 \tag{6}$$

The mass transport equation in porous media becomes:

$$\nabla\left(\rho_g \varepsilon_g u_g y_{gi}\right)-\nabla\left(\rho_g D_{gi} \varepsilon_g \nabla y_{gi}\right)=S_{gi} \tag{7}$$

and the Stefan-Maxwell equations remain the same:

$$\nabla x_{gi}=\sum\frac{x_{gi}.x_{gj}}{D_{ij}^{eff}}(v_i-v_j) \tag{8}$$

where the binary diffusivities D_{ij}^{eff} have been corrected for the porosity. This was done by applying the so-called Bruggemann correction:

$$D_{ij}^{eff}=D_{ij}\varepsilon_g^{1.5} \tag{9}$$

Finally, the energy equation in the diffusion layer is given:

$$\nabla(\rho_g \varepsilon_g u_g C_p T_g-\lambda_g \nabla T_g)=\varepsilon_g \beta(T_g-T_s) \tag{10}$$

where the term on the right hand side accounts for the heat transfer from the solid matrix to the gas phase. β is a modified heat transfer coefficient that accounts for the convective heat transfer in [W/m^2] and the specific surface area [m^2/m^3] of the porous medium. Hence, the unit of β is [W/m^3]. βIn the solid matrix of the gas-diffusion layer, heat transfer is calculated via (Berning et al., 2002):

$$\nabla(\lambda_s \nabla T_s)=\varepsilon_g \beta(T_s-T_g) \tag{11}$$

3.3 Analysis of model

In this study, the model presented is a 3-D, isothermal, single-phase, steady-state model that resolves coupled transport processes in membrane, catalyst layers, gas diffusion layers and reactant flow channels of a PEM fuel cell. The computational domain (Figure 3) is divided into 94,080 cells. The governing transport equations are solved subject to the various boundary conditions presented in the preceding section using the Fluent 14.0 CFD code. Fluent 14.0 is a parallel code using a finite volume method and an iterative segregated implicit solver. Boundary conditions are set as follows: constant mass flow rate at the channel inlet and constant pressure condition at the channel outlet. At the below, geometrical, physical and electrochemical parameters used in study are given in Table 1 and Table 2.

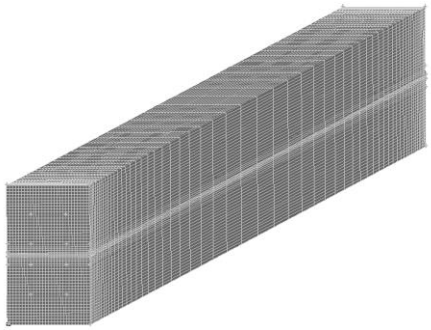

Figure 3: Fuel cell geometry and computational domain

Table 1: Geometrical Parameters

Parameters	Value (mm)
Channel depth	1
Channel width	0.8,1,1.2
Channel length	125
Gas diffusion layer thickness	0.27
Catalyst layer thickness	0.02
Membrane thickness	0.127

4. Results and discussions

The channel width has a large impact on the local current density distribution. An increase in the width of the gas flow channel means that the velocity of the incoming gas has to be decreased with all remaining parameters remaining constant, and this will decrease the gases velocity in the gas diffusion layer and hence, reduced the current density. Analysis of the channel width, in the range of 0.8–1.2 mm, on the fuel cell performance is shown in Figure 4a. Operation temperature and pressure are set to be at 343 K and 1 atm. Nafion 115 (0.127 mm) membrane is used. The effect of channel width on the fuel cell performance becomes more important at high current density applications. It can be seen from Figure 4a that increasing the channel width while the cell width remains constant decreases the current density.

Table 2: Physical and Electrochemical Parameters

Parameters	Value	Units
Gas diffusion layer porosity	0.3,0.4,0.5,0.6	-
Catalyst layer porosity	0.5	-
Gas diffusion layer viscose resistance	$1\cdot10^{12}$	1/m²
Anode reference exchange current density	7,500	A/m²
Cathode reference exchange current density	20	A/m²
Electrolyte area	0.003	m²
Open circuit voltage	0.95	V
Operation pressure	101,325	Pa
Operation temperature	323,333,343	K
Cathode mass flow rate	$5.0\cdot10^{-6}$	kg/s
Anode mass flow rate	$6.0\cdot10^{-7}$	kg/s

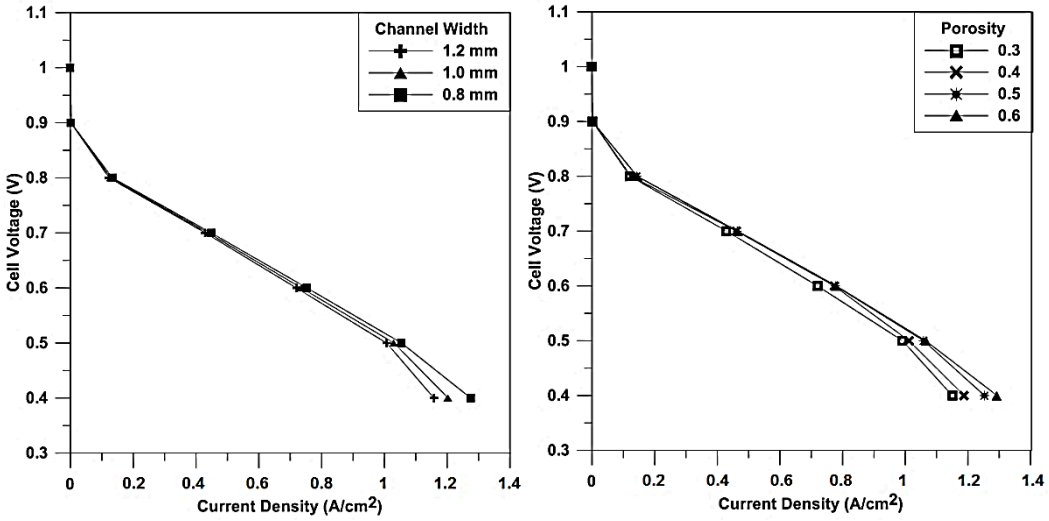

Figure 4: a) Effect of PEM fuel cell channel width, b) Effect of GDL porosity

The effect of gas diffusion layer porosity in the range $0.3 \leq \varepsilon \leq 0.6$ on current density distribution is investigated in this study. An increase in porosity enhances the diffusion transport of the reactant gas through the porous layers and, in turn, increases the local values of the current density. Obviously, fuel cell performance depends on the GDL porosity. In Figure 4b the *I–V* curves demonstrate that a better performance can be obtained by using a gas diffusion layer of higher porosity. A gas-diffusion layer of higher porosity has an ability of stronger diffusion transport, which is beneficial in that it supplements the reactant gas to the catalyst layer. Increasing operation temperature is helpful to enhance electrochemical reaction rate and ionic transport in PEMFC, and the cell performance. The studies also confirm these results. When the PEMFC is operated at high temperatures, the cell voltage increases and more hydrogen is consumed, increasing the cell efficiency (Authayanun et al., 2013). However, operation temperature should not be higher than 363 K, or PEMFC may be damaged due to overheating. From the results shown in Figure 5, it is observed that, as the cell temperature increased from 323 K to 343 K, current density increases and the cell performance is enhanced (channel width is 1.2 mm, pressure is 1 atm. and membrane is Nafion 115).

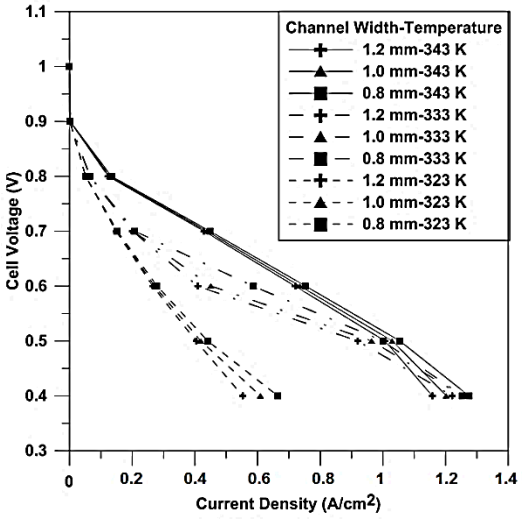

Figure 5: Effect of PEM fuel cell temperature on current density

5. Conclusions

A theoretical, three-dimensional, isothermal model has been developed to investigate the effects of diffusion layer porosity with different channel width on performance of a PEMFC. Using a single-phase, steady-state, three-dimensional flow simulation of PEM fuel cell, the following conclusion was obtained; an increase in porosity

enhances the diffusion transport of the reactant gas through the porous layers and, in turn, increases the local values of the current density. Obviously, cell performance depends on the GDL porosity. In literature, it was also resulted that it is easy to improve the fuel cell performance for higher porosity in the diffusion layer by speeding up the gas diffusion, reducing the concentration grads of gas, depressing the ridge board domino effect and falling current density grads at a 3-D, steady-state non-isotherm mathematical model for PEMFC (Wei et al., 2011). Also it is found that smaller sized channels (narrow channel width) are required to obtain higher current densities. When the flow channel width is small, water can easily diffuse from the corner to the middle of the channel to hydrate the membrane, thus the cell performance increases. From the studies it is seen that the reduction of GDL porosity from 0.6 to 0.3 results in a 4.01 % decrease in the current density at 0.4 V.

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