NUMERICAL INVESTIGATION OF BACKPRESSURE AND FLOW CHANNEL CHARACTERIZATION EFFECTS IN PEM FUEL CELL

Mert TAŞ, Canan YILDIRIM, Gülşah ELDEN*
Department of Energy Systems Engineering, Erciyes University, Kayseri, Turkey
*Corresponding author: Gülşah Elden, e-mail: gulsah@erciyes.edu.tr

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ABSTRACT

The purpose of this study is to investigate the effects of channel width/depth (W/D) ratio on cell performance and species transport associated with back pressure for Polymer Electrolyte Membrane fuel cell. In line with this purpose, firstly, to analyze the effect of back pressure on fuel cell performance, the back pressure is increased gradually from 1.25 atm to 2 atm. Secondly, channel width/depth ratio is increased from 1 to 2.5 (step by 0.5) to bring out the effect of channel width/depth ratio on cell performance and mass transport at the constant value of backpressure (2 atm). Consequently, the increments back pressure and channel Width/Depth ratio positively affects to fuel cell performance.

Keywords:
PEM Fuel Cell, Back Pressure, Channel Width Ratio, 3D Numerical Modeling

1. INTRODUCTION

Polymer electrolyte membrane (PEM) fuel cells are devices that convert the chemical energy to electrical energy efficiently. PEM fuel cells have promising properties such as high power density, scalability, eco-friendly, transportable and low operating temperatures.
Fuel cell's geometric properties and operation conditions have a great impact on their performance. Dimension of fuel cell components and active area, operating temperature, and relative humidity value are instances for their specific properties. Moreover, channel dimensions, ratios of width and height, backpressure of reactants can affect the performance of PEM fuel cell.
Wang X-D. et al [1], computed on PEM fuel cell that 3D, two phase and anisothermal model. They optimized the channel size of PEM fuel cell with serpentine flow field. Choi K-S. et al [2] studied about optimization of serpentine channel of PEM fuel cell. The researchers find out the optimum dimensions of the serpentine flow channels according to the results of temperature, water, pressure and current density distribution. Muthukumar M. et al [3]. modelled a 3D PEM fuel cell with the aim of reveal that the effect of different height and width on PEM fuel cell performance. But they also did not examine the effect of backpressure effect on PEM fuel cell. In literature, wide a range of study about fluid channel characterization of PEM fuel cells are attainable [4-7].

Sreenivasulu B. et al conducted experimental study of the effect of backpressure and flow channel geometry on PEM fuel cell performance [8]. Zhang J. et al studied the effect of backpressure on PEM fuel cell performance and reactions [9]. They investigated that backpressure affect the open circuit voltage (OCV) and performance. Rohendi D. et al studied the degradation effects of backpressure and temperature on PEM fuel cell. They investigated that backpressure has decreased the performance degradation and improved the conductivity of fuel cell [10]. Wide a range of study about backpressure effects on PEM fuel cell are attainable in literature [11-15].

The researchers studied the effect of backpressure on PEM fuel cell regardless to different cross-sectional flow channel type.
But in fact, studies that researching the effect of together of them are limited. With the aim

of filling the gaps in literature, this study has been conducted.

2. MATHEMATICAL MODELING

The effects of channel width/depth (W/D) ratio on cell performance and species transport associated with back pressure for Polymer Electrolyte Membrane fuel cell are investigated in this study. Three dimensional (3D) numerical model including mass, momentum and charge equations is developed to investigate thoroughly these effects. The 3D model shown in Figure 1 consists of anode/cathode gas channels, anode/cathode gas diffusion layers, anode/cathode catalyst layers and Nafion membrane.

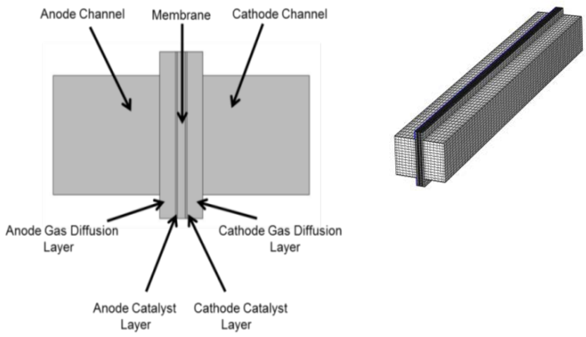

Figure 1. Schematic illustration of PEM fuel cell (a) PEM fuel cell components (b) Mesh of 3D domain [16].

2.1 Model Assumptions and Equations

The aim of this study is to investigate the effect of not only channel width/depth ratio but also on back pressure (PEM) fuel cell performance. The developing 3D model to achieve this aim is solved conservation equations given in Table 1under the following assumptions by using *COMSOL Multiphysics 4.2a* software.

- The process is in steady state.
- Cell temperature is constant.
- Hydrogen, oxygen and water are in gas phase and all gases are assumed in ideal gas.
- Porous structures (gas diffusion layers, catalyst layers and membrane) are isotropic in all directions.
- Contact resistances are ignored within fuel cell.

Table 1. Conservation Equations

Continuity equation	$\nabla(\varepsilon\rho\vec{u}) = 0$
Navier Stokes Equation	$\nabla(\varepsilon\rho\vec{u}\vec{u})=-\varepsilon\nabla P+\nabla*\left(\varepsilon\mu^{eff}\nabla u\right)+S_u$
Darcy Law	$u=-\frac{k_p}{\mu}$
Stephan-Maxwell equation	$\rho\vec{u}\nabla m_i=\nabla\left[\rho\varepsilon m_i\sum_{j=i}^{N}D_{ij}\left\{\frac{M}{M_i}\left(\nabla m_i+m_i\frac{\nabla M}{M}\right)\right\}\right]$
Charge conservation equation	$\nabla.(k_e^{eff}\nabla\Phi_e)+S_\Phi=0$

<u>Boundary Conditions:</u>

To solve the differential equations in Table 1, boundary conditions are used as follows;

For continuity and momentum equations; at anode gas flow channel inlet; U_a, at cathode gas flow channel inlet; U_c, at anode gas flow channel outlet; $P_{a,backpressure}$, at cathode gas flow channel outlet; $P_{c,backpressure}$.

For Stephan-Maxwell equation; at anode gas flow channel inlet; $w=w_{H2}$, at cathode gas flow channel inlet; $w=w_{O2}$, $w=w_{H2O}$, at the other boundaries of the cell;

$$\frac{\partial c_{H_2,H_2O}}{\partial n}=0\,.$$

For charge transport; at anode bipolar plate; $\phi_s=0$, at cathode bipolar plate; $\phi_s=V_{oc}$, at the external boundaries of the cell;

$$\frac{\partial\phi_e}{\partial n}=0\,,\frac{\partial\phi_s}{\partial n}=0\,.$$

The dimensions of porous structures within PEM fuel cell and the value of transfer parameters are listed in Table 2 and Table 3, respectively.

Table 2. The dimensions of porous structure

Structure	Value
Gas diffusion layers	315 μm
Catalyst layers	50 μm
Membrane	51 μm

Table 3. The value of transfer parameters

Parameters	Value
Cell Temperature	353 K
Inlet H_2 mass fraction	0.8
Inlet H_2O mass fraction	0.023
Inlet oxygen mass fraction	0.25
Hydrogen molar mass	0.002 kg mol^{-1}
Nitrogen molar mass	0.028 kg mol^{-1}
Water molar mass	0.018 kg mol^{-1}
Oxygen molar mass,	0.032 kg mol^{-1}
H_2-H_2OBinary diffusion coefficient	9.15e-5·$(T/307.1)^{1.75}$ $m^2\,s^{-1}$
N_2-H_2OBinary diffusion coefficient	2.56e-5·$(T/307.15)^{1.75}$ $m^2\,s^{-1}$
O_2-N_2 Binary diffusion coefficient	2.2e-5·$(T/293.2)^{1.75}$ $m^2\,s^{-1}$
O_2-H_2OBinary diffusion coefficient	2.82e-5·$(T/308.1)^{1.75}$ $m^2\,s^{-1}$
Oxygen reference concentration	40.88 mol m^{-3}
Hydrogen reference concentration	40.88 mol m^{-3}
Gas diffusion layer permeability	8.97e-12 m^2
Gas diffusion layer electrical conductivity	200 S m^{-1}
Gas diffusion layer porosity	0.47
Catalyst layer permeability	1.8e-12 m^2
Catalyst layer porosity	0.23

3. RESULTS AND DISCUSSION

The performance test is performed for a single PEM fuel cell with 25 cm^2 active surface area to validate numerical model. When the experimental data and numerical data are compared with each other, it is seen that from Figure 2, the data are compatible with each other.

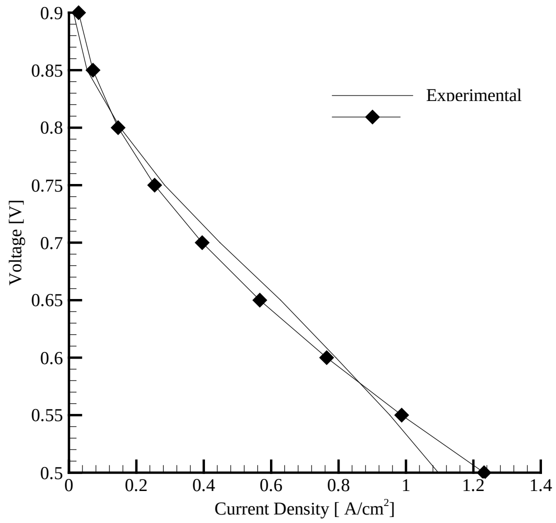

Figure 2. Validation of numerical model

The numerical calculations are carried out to analyze the effects of width/depth (W/D) ratio on cell performance and species transport associated with back pressure for Polymer Electrolyte Membrane fuel cell. Firstly, to analyze the effect of back pressure on fuel cell performance, the back pressure is increased gradually from 1.25 atm to 2 atm. Lastly, channel width/depth ratio is increased from 1 to 2.5 (step by 0.5) to bring out the effect of channel width/depth ratio on cell performance and mass transport at the constant value of backpressure (2 atm).

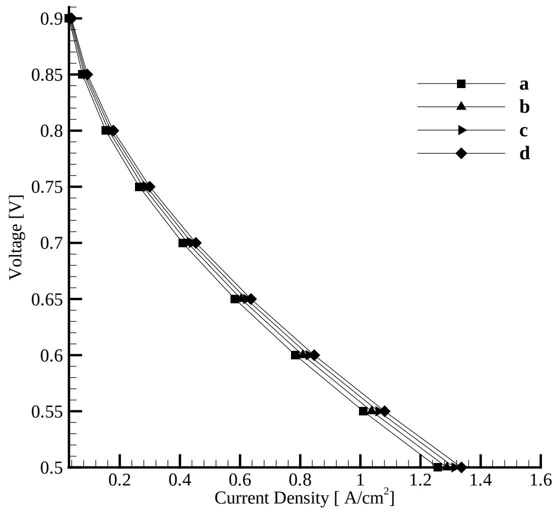

Figure 3. The variation of polarization curves for different back pressure (BP), (a) BP=1.25 atm, (b) BP=1.5 atm, (c) BP= 1.75 atm, (d) BP= 2 atm, W/D=1, P_{inlet}= 3 atm.

The polarization curves for different back pressure are shown in Figure 3. As the fuel cell performance increases with increasing back pressure, the current density ranges approximately from 1.26 A/cm^2 to 1.34 A/cm^2. The variation of polarization curve depending of different width/depth ratio is illustrated in Figure 4. As shown this figure, when the channel width/depth ratio ranges from 1 to 2.5 at constant inlet and back pressures, activation and ohmic polarizations are more affected than concentration polarization. Ohmic and activation polarizations significantly improve due to decreasing of the losses into fuel cell.

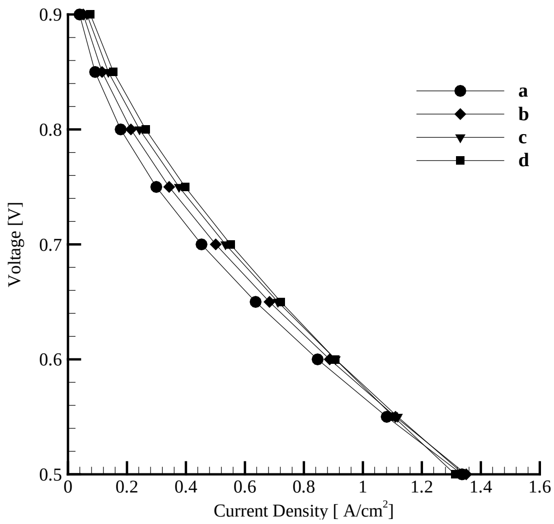

Figure 4. The variation of polarization curves for different channel width/depth ratio (W/D), (a)W/D=1, (b)W/D=1.5, (c) W/D=2, (d) W/D=2.5, P_{inlet}= 3 atm and BP=2 atm.

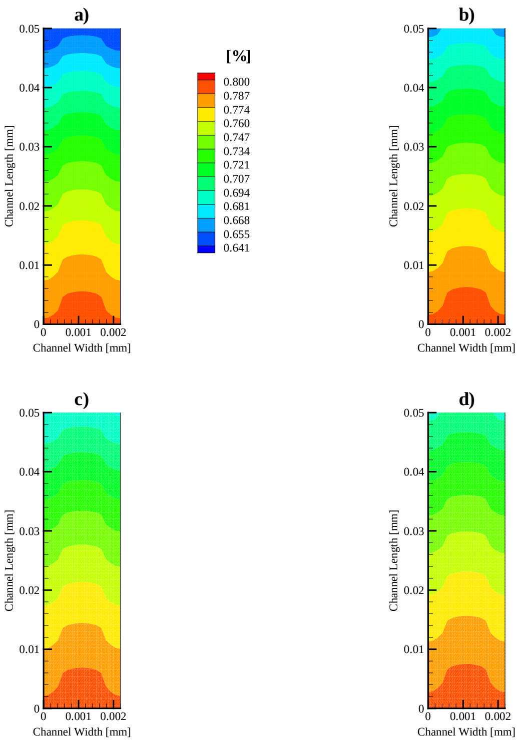

Figure 5. The variation of H_2 mass fraction depending on back pressure (BP) at 0.5 V, W/D=1 and P_{inlet}=3 atm (a) BP=1.25 atm, (b) BP=1.5 atm, (c) BP= 1.75 atm, d) BP= 2 atm.

The variations of H_2, H_2O and O_2 mass fractions through surface in between gas channels and gas diffusion layers for the different back pressure are demonstrated in Figure 5, Figure 6 and Figure 7, respectively. As it is obviously seen in the figure, the increment in back pressure affects the most H_2 diffusivity rather than the other gasses.

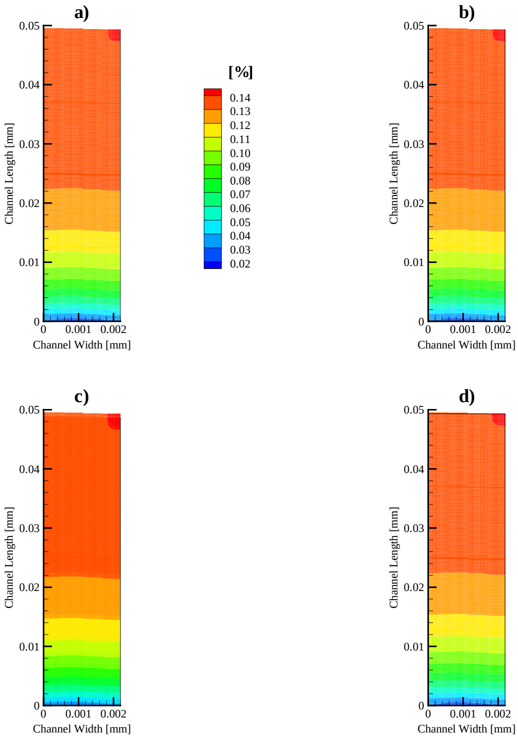

Figure 6. The variation of H_2O mass fraction depending on back pressure (BP) at 0.5 V, W/D=1 and P_{inlet}=3 atm (a) BP=1.25 atm, (b) BP=1.5 atm, (c) BP= 1.75 atm, d) BP= 2 atm.

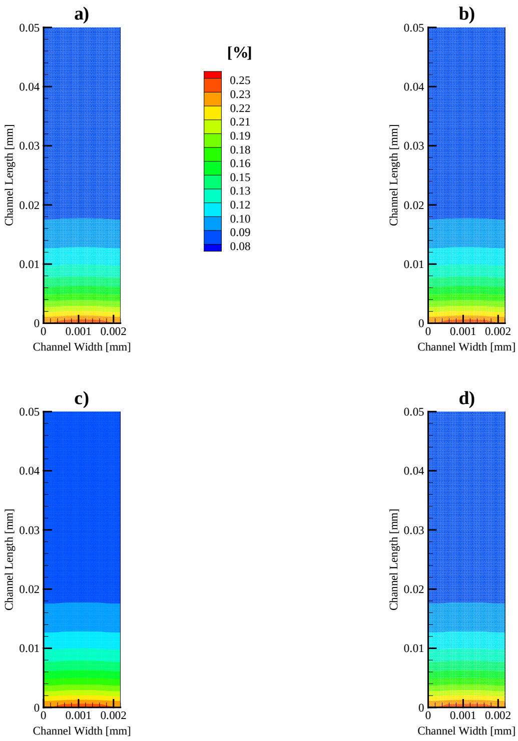

Figure 7. The variation of O_2 mass fraction depending on back pressure (BP) at 0.5 V, W/D=1 and P_{inlet}=3 atm (a) BP=1.25 atm, (b) BP=1.5 atm, (c) BP= 1.75 atm, d) BP= 2 atm.

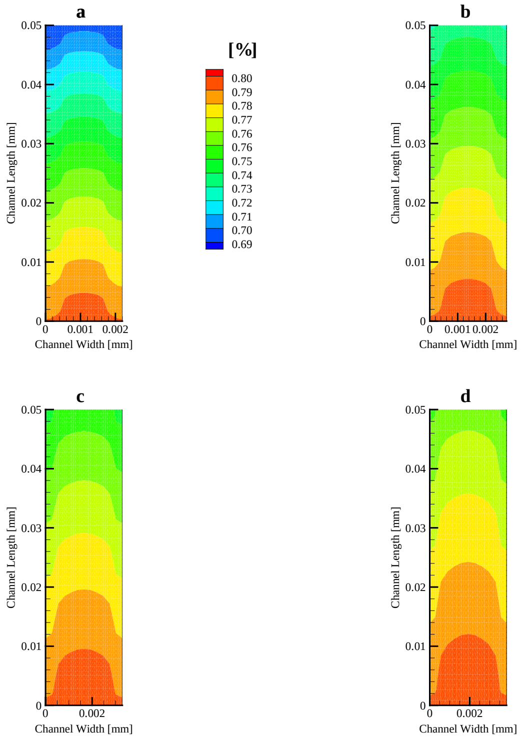

Figure 8. The variation of H_2 mass fraction depending on channel Width/Depth ratio (W/D) at0.5 V, P_{inlet}=3 atm and BP=2 atm, (a) W/D=1, (b) W/D=1.5, (c) W/D=2, (d) W/D=2.5.

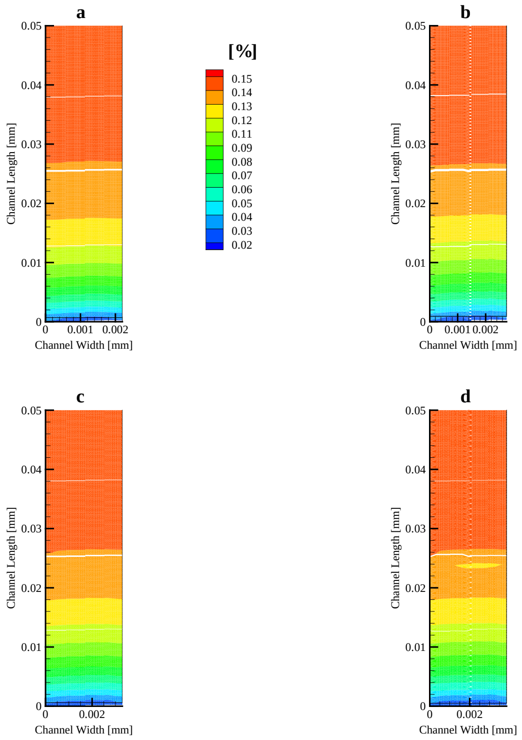

Figure 9. The variation of H_2O mass fraction depending on channel Width/Depth ratio (W/D) at0.5 V, P_{inlet}=3 atm and BP=2 atm, (a) W/D=1, (b) W/D=1.5, (c) W/D=2, (d) W/D=2.5.

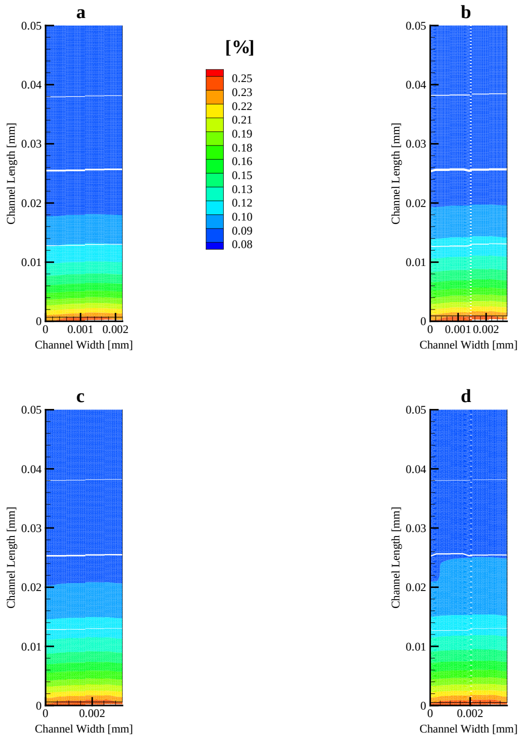

Figure 10. The variation of O_2 mass fraction depending on channel Width/Depth ratio (W/D) at0.5 V, P_{inlet}=3 atm and BP=2 atm, (a) W/D=1, (b) W/D=1.5, (c) W/D=2, (d) W/D=2.5.

Figure 3 shows the variation of H_2 mass fraction depending on channel Width/Depth ratio. As the channel Width/Depth ratio is increases from 1 to 2.5, the distribution of H_2 mass fraction through surface in between gas channels and gas diffusion layers increases. Figure 9 and 10 respectively indicate the variations of H_2O and O_2 mass fractions for four different channel Width/Depth ratio. The distributions of H_2O and O_2 mass fractions through gas channel slightly change with increasing Width/Depth ratio.

4. CONCULUSION

In this study, the effects of width/depth (W/D) ratio on cell performance and species transport associated with backpressure for Polymer Electrolyte Membrane fuel cell are investigated. Consequently, the increments back pressure and channel Width/Depth ratio positively affects to fuel cell performance. Furthermore, the distributions of H_2 mass fraction through gas channel significantly change according to the distributions of H_2O and O_2 mass fraction through it in the increment back pressure as well as Width/Depth ratio.

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Nomenclature

BP	Back Pressure
C_a	Species Concentration
D_{a-b}	Binary Diffusion Coefficient
K_a	Species Permeability
M_a	Species Molar Mass
U	Velocity
P	Pressure
W_a	Species Mass Fraction
W/D	Width/Depth Ratio

Greek Letters

σ	Electrical or ionic conductivity

ε	Porosity
ϕ	Potential
ρ	Density

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