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Investigating the effect of the geometry of gas injection channels on the performance and dynamic behavior of the polymer electrolyte membrane fuel cell

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Abstract

The polymer membrane fuel cell, which works with hydrogen and air and has high efficiency and power density, low-temperature operation, and the ability to start quickly and without pollution, can be a good alternative to fossil fuels. The performance of a proton exchange membrane fuel cell is highly dependent on the geometry, flow channel configuration, and size. In this numerical study, the performance of the polymer membrane fuel cell has been investigated by investigating the performance based on the design of gas injection channels with different geometries in an unsteady state. The computational fluid dynamics method has been used to solve the governing equations. In this method, the finite volume method is used to discretize and solve the equations. Different geometries have been used for this research, including pseudo-spiral (case A), parallel (case B), and pin (case C), whose dimensions are the same as the spiral base model. Using dynamic simulation, it was observed that after about 70 seconds, the flow reached a stable state, and water production gradually increased. The results show that case C performs better than other models, and case B shows the worst performance.

Keywords: Polymer Membrane Fuel Cell; Numerical Modeling; Dynamic Behavior; Gas Channel Geometry.

1. Introduction

Energy supply is one of the main concerns of human today. Fossil fuels are one of the main sources of energy supply. The most important drawback of fossil fuels is their perishability. The next issue regarding these fuels is that they cause environmental pollution (global warming, climate change, melting polar ice caps, acid rains, pollution, damage to the ozone layer, etc.) [1]. Using clean energy instead of limited fossil energy can solve the challenges. Proton membrane fuel cell is a new source of energy for transportation and... [2]. High efficiency, high power density, high operating temperature, and environmental compatibility advantages significantly increase the applicability of polymer fuel cells in the automotive industry compared to other fuel cells [3]. Many researchers have focused on enhancing fuel cell performance in various aspects and compared their experimental results with studies by Amphlett et al. and Kim et al. [4, 5]. The effect of stoichiometry on the dynamic behavior of the polymer membrane fuel cell under variable loads has been considered in many works that this transient analysis is potentially attractive in automotive and stationary applications and flow field design [6-8]. Watana et al presented a dynamic equivalent circuit model for PEMFC gas permeation layers. The gas diffusion layer is an important part of PEMFC [9]. In a study, Ahmadi et al. investigated the effect of inlet gas humidity on fuel cell performance [10]. Zhang et al.[11] carried out a system simulation model considering nitrogen confluence and water transport, which is in good agreement with the experimental results. Also, Ahmadi et al. investigated the geometric effect of the injection channels on the performance of a polymer fuel cell in steady state [12].

The current research is a numerical study that investigates the performance of the polymer membrane fuel cell based on the design of gas injection channels with different geometries in unsteady state. Various geometries have been used for this research, including pseudo-spiral, parallel, and pin, which are validated with the spiral base model. The most important goal of this research is to pay attention to the new designs of the polymer membrane fuel cell and change the parameters for its better performance.

2. Mathematical model

Figure 1 shows an overview of the basic fuel cell model. This model includes porous gas diffusion layers, polymer electrolyte membrane, catalyst layers, spiral gas channels and bipolar plates on both sides of cathode and anode. Table 1 shows the geometric characteristics of the model.

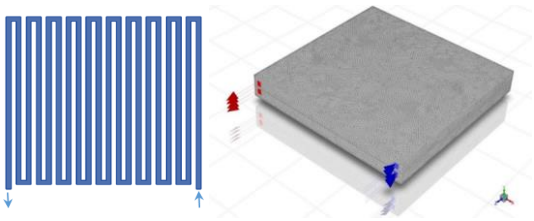


Figure 1. Basic fuel cell model

Table 1. Geometric characteristics of the basic model [5]

Parameters	Value
Channel height	1×10^{-3} m
Channel width	0.8×10^{-3} m
Channel area	8×10^{-7} m^2
Effective land area	11×10^{-4} m^2
CL thickness	0.03×10^{-4} m
GDL thickness	2.5×10^{-4} m
Membrane thickness	0.5×10^{-4} m

3. Assumptions and governing equations

It was assumed that:

- The input and output gases of the fuel cell, including hydrogen, oxygen, and water, were ideal gases,
- The gas flow was incompressible,
- The fuel cell is assumed to be steady-state,
- The bipolar anode and cathode plates and the gas inflows of the anode and cathode channels have constant temperatures,
- The present model is assumed to be a three-dimensional and multi-phase model
- The membrane was completely impermeable to the reactant gases.

The governing equations are: continuity, momentum, species and potential. In the first equation, the density of the mixture is expressed as ρ.ε, and the viscosity of the gas mixture is shown as μ in the kinetic equation. Su is the source of the equation of motion and is used to describe the Darcy drag flow through porous gas diffusion layers and catalyst layers. More information about the governing equations and boundary conditions is available in [2].

4. Solving process

To solve the equations governing the fuel cell, Fluent software has been used. This simulation program uses the finite volume method to discretize and solve the equations. To obtain a stable solution, the upstream method with first-order accuracy is used to solve the conservation equations for energy, species and momentum at the beginning of the solution process. After several repetitions, the accuracy of solving the equations should increase to the second order. A simple algorithm has been used to couple pressure and speed [13]. The solution algorithm is shown in Figure 2.

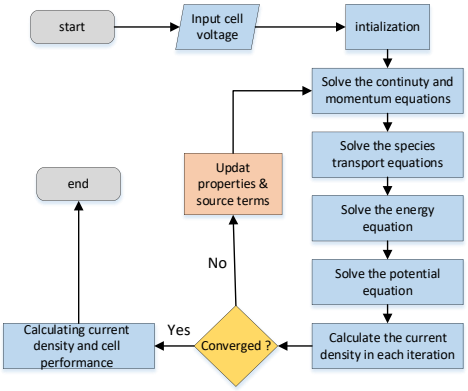


Figure 2. solution algorithm

5. Validation

As seen in Figure 3, the optimal number of computing cells is approximately 500,000.

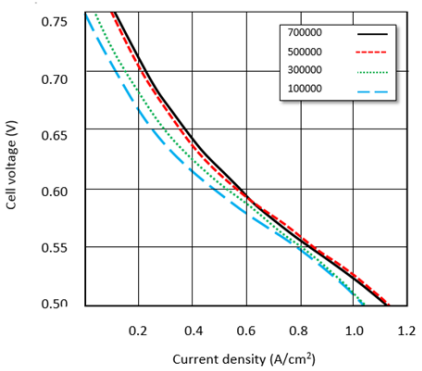


Figure 1. mesh independence

As can be seen in Figure 4, the results of the multi-phase simulation are closer to the real conditions, the cell voltage is slightly lower than the single-phase conditions, and the results of the basic model are close to Jeon's results, which indicates a correct and reliable method [14].

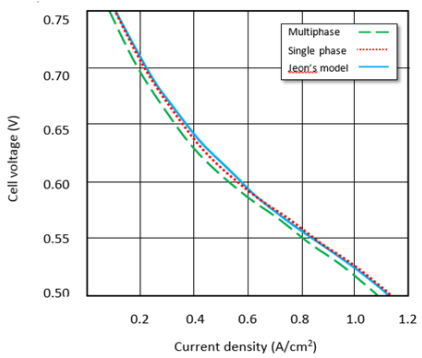


Figure 2. Polarization curve of model validation

6. Results and discussion

In the present study, three different flow field geometries have been numerically analyzed in comparison with the basic model. The base model is spiral and cases A, B and C are semi-spiral, parallel and pin, respectively (Figure 5).

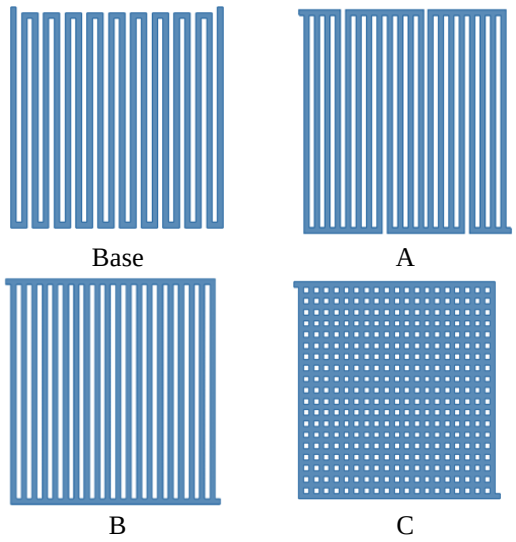


Figure 5. The geometries studied in this research.

In general, the assumptions and boundary conditions are the same to show the most optimal flow state. Parameters and operating conditions are selected according to Jeon model conditions shown in Table 2.

Table 2. Parameters and performance conditions

Parameters	Value
Mass fraction of H_2 at anode inlet	11.5 %
Mass fraction of H_2O at anode inlet	88.5 %
Mass fraction of O_2 at cathode inlet	18.3 %
Mass fraction of H_2O at cathode inlet	21.5 %
Mass flow rate at anode inlet	$7.13265e^{-7}$ kg/s
Mass flow rate at cathode inlet	$6.1064e^{-6}$ kg/s
Relative humidity (%)	100
Open circuit voltage	0.96 V
Pressure	101 kPa
Temperature	353 K

The diagram in Figure 6 shows the polarization curve for different models at 0.6 V. Numerical results show that case C produces more current density and output power compared to other models, and case B has the lowest value.

In this section, the dynamic mode of the fuel cell for different models has been investigated. Figure 7 shows the average current density over time for different models. As it is known, the current in these models reaches a stable state after about 70 seconds. The time step considered for dynamic analysis is equal to 10^{-5}.

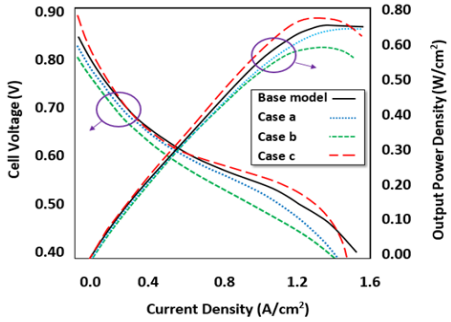


Figure 3. Polarization curves of different models

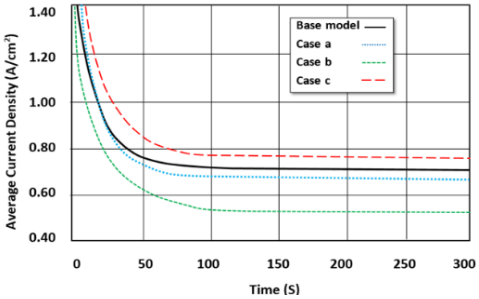
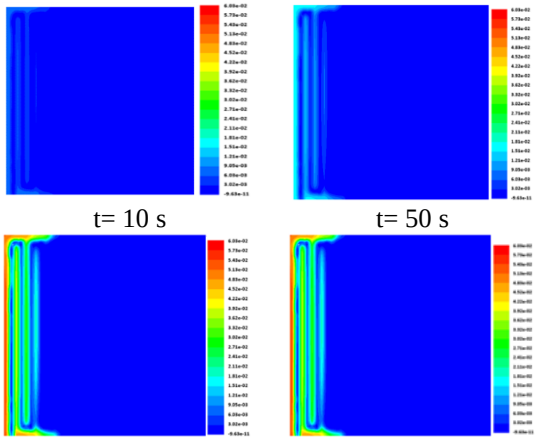


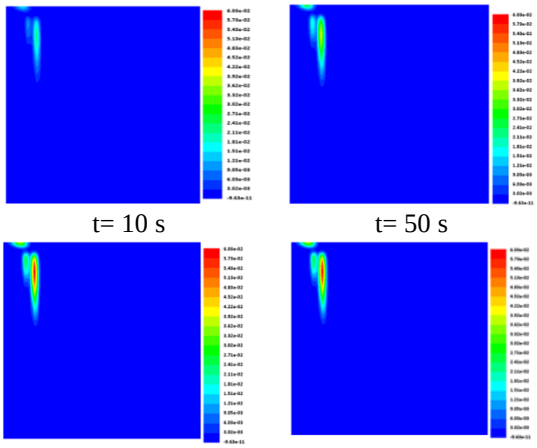
Figure 7.Diagram of current density with time for different models

Figure 8 shows the production of liquid water on the cathode side in dynamic mode for different models. It can be seen that case B produces the most liquid water. Therefore, it causes flooding phenomenon and causes battery failure. On the other hand, case C has the lowest amount of liquid water production, which indicates the best mode to prevent performance reduction and damage in the battery. According to the models, it can be seen that with the passage of time and increased activity related to the fuel cell, all models have water production. Water production in a polymer fuel cell is due to the electrochemical reaction between H+ ions and oxygen. Also, some water molecules migrate from the anode side to the cathode side along with H+ ions. Therefore, in the polymer fuel cell, with the passage of time, the amount of water accumulates on the cathode side and will show an increase. As it was said earlier, the higher the amount of water accumulation in a model, the rate of penetration of species into the reaction areas and consequently the level of activity and performance of that model will decrease. According to Figure 8, it is clear that case B shows a relatively higher amount of water accumulation compared to all models. This is due to the fact that this type of channel arrangement initially has a high level of activity and consequently a higher amount of water production, but due to the type of channel arrangement, it has a large friction loss and this prevents the movement and discharge of liquid water. This causes the mentioned model to have a low level of performance in steady state and the need for water management in this model is more. In contrast to mode C, it has less water accumulation and therefore has better performance than other models. The network arrangement of mode C causes the transfer of water from the cathode to the

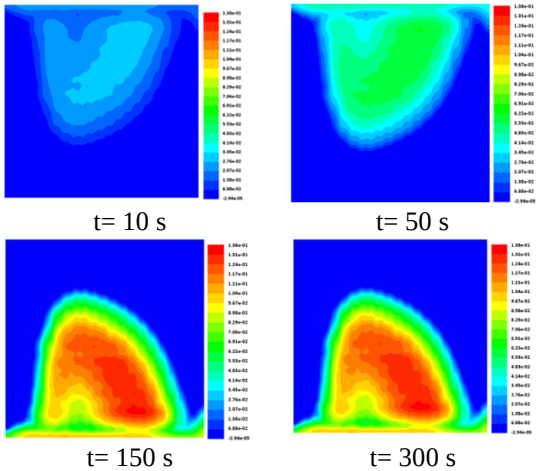
outside of the fuel cell at a faster rate, and as a result, the performance of the cell will increase. Therefore, the performance of this mode is better than all modes.



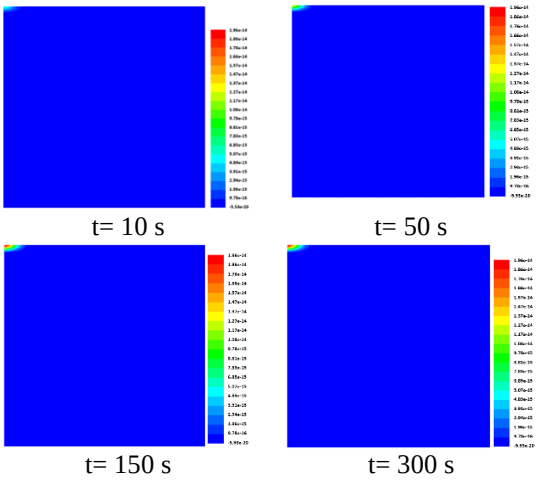
Base model



Case A



Case B



Case C

Figure 8. Production of liquid water

7. Conclusions

In the current study, pseudo-spiral, parallel and pin models of polymer membrane fuel cells were compared with the spiral base model. Then, the models were simulated using computational fluid dynamics and finite volume methods. This model was verified by comparison with previous works. It was found that the proposed model is in good agreement with previous studies. Using dynamic simulation, it was observed that after about 70 seconds, the flow reached a steady state and water production gradually increased. Furthermore, it approached the steady state. Finally, it can be said that case C performs better than other models and improves the performance of a polymer membrane fuel cell. The present study can help manufacturers in designing gas flow channels. It is suggested that future research develops new fuel cell geometries and investigates their performance.

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