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Performance Investigation of PEM Fuel Cell with Three-Pass Serpentine Flow Fields under Varying Operating Voltages

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ABSTRACT

The fuel cells performance is significantly impacted by both design and operational factors. The effective distribution of reactants within the flow fields is facilitated by the design of the flow channels. Therefore, the geometry of the flow channels and the overall design of the flow field play a crucial role in determining the fuel cells performance. Among various flow field designs, the serpentine flow field demonstrates superior performance compared to others. In this research, a three-dimensional proton exchange membrane fuel cell model was developed and used to study the influence of three-pass serpentine flow field on cell performance across varying operating voltages (0.9 V, 0.7 V and 0.5 V). The purpose of this research is to simulate and evaluate the comportment of the three-pass serpentine flow channels configuration by analyzing several parameters such as channels velocity distribution, oxygen mole fraction, pressure distribution and electrolyte current density along the z-axis at the cathode under different operating voltages. Numerical simulations were conducted using the COMSOL Multiphysics software. Therefore, this software is used to solve numerically the complete three-dimensional model with the governing equations of charge conservation, species transport, momentum, and continuity. The obtained results indicate that among different operating voltages, the cell voltage of 0.5 V demonstrated the highest channels velocity distribution, pressure distribution, and electrolyte current density. Moreover, it is found that at an operating voltage of 0.5 V, there is an important decrease in oxygen concentrations indicating a significant oxygen consumption in the fuel cell which improves the overall efficiency. This work contributes valuable insights to the optimization of fuel cell performance, specifically highlighting the favorable outcomes associated with the three-pass serpentine flow field design at lower operating voltages.

1. Introduction

Fuel cell technology has emerged as a promising alternative to traditional energy sources owing to its efficiency, low emissions and versatility [1-7]. Among the various types of fuel cells, Proton Exchange Membrane Fuel Cells (PEMFCs) have gained significant attention because of their quick start up time, high power density, and suitability for numerous applications [8-10]. Enhancing the

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performance of PEMFCs is crucial for their widespread adoption, and one approach is through the optimization of the flow field design [11-14]. This plays a critical role in the fuel cells performance by facilitating uniform reactant distribution, efficient product removal and minimizing pressure losses [15, 16].

The serpentine flow field design has garnered considerable interest because of its ability to enhance mass transport within the fuel cell and promote uniform reactant distribution uniformity [17, 18]. Researchers worldwide have extensively studied the PEMFCs with three-pass serpentine flow fields design, investigating its potential to enhance cell performance and fuel utilization [19].

In recent years, significant progress has been made in understanding the advantages of the three-pass serpentine flow fields design. Studies have demonstrated that this configuration provides several benefits [20]. First, the serpentine pattern ensures at uniform distribution of reactants across the electrode surface, reducing the concentration gradients and enhancing the overall cell performance. Second, multiple passes through the flow channels increase the residence time, enabling improved reactant utilization and reduced waste. Finally, the serpentine design facilitates effective water management, ensuring efficient removal of product water, which is crucial for maintaining optimal fuel cell performance.

An investigation of fuel cells performance using various flow field configurations has been a subject of experimental and computational studies [21-24]. Indeed, researchers such as Caglayan *et al.,* [25] designed a 3D PEMFC numerical model with 25 cm^2 active area and examined the cell's performance using a single and triple-mixed serpentine flow field. The triple mixed serpentine flow channel outperformed the single serpentine flow channel, according to their findings. In order to investigate the impact of sub-rib convection on performance at different channel aspect ratios, Wang *et al.,* [26] designed 3D PEMFC models with triple and single serpentine flow channels. They demonstrated that the single serpentine flow field performance was mostly unaffected by a modifying in the aspect ratio of the channel, but the triple serpentine flow field performance was significantly affected. For PEMFC applications, Suresh *et al.,* [27] created a new serpentine flow channel with improved cross-flow and conducted both experimental and computational investigations. They minimized the pressure drops while attaining a consistent flow distribution.

The PEMFC performance study is very useful in the field of energy research and is crucial for advancing fuel cell technology.

In the present work, a 3D mathematical model is used to investigate the PEMFC performance with three-pass serpentine flow fields using the Electrochemistry Module of COMSOL Multiphysics software. The purpose of this study is to analyze various parameters, including channels velocity distribution, oxygen mole fraction, pressure distribution and electrolyte current density at the cathode in the z-direction. The model is used to simulate and assess the PEMFC dynamic behavior of under different operating conditions, specifically at voltages of 0.9 V, 0.7 V and 0.5 V.

2. Methodology

2.1 Geometric Model

The three-dimensional model of PEMFC with 3-pass serpentine flow channels is shown in Figure 1. This model comprises three channel regions on the cathode (oxygen) side, cathode Gas Diffusion Layer (GDL), cathode Gas Diffusion Electrode (GDE), membrane, anode GDE and anode GDL on the anode (hydrogen) side. The channel inlets are on the left, while the channel outlets are on the right. The anode flow channels, which are not part of the model geometry, are faced by the bottom anode GDL boundary. The geometric parameters of the model are presented in Table 1.

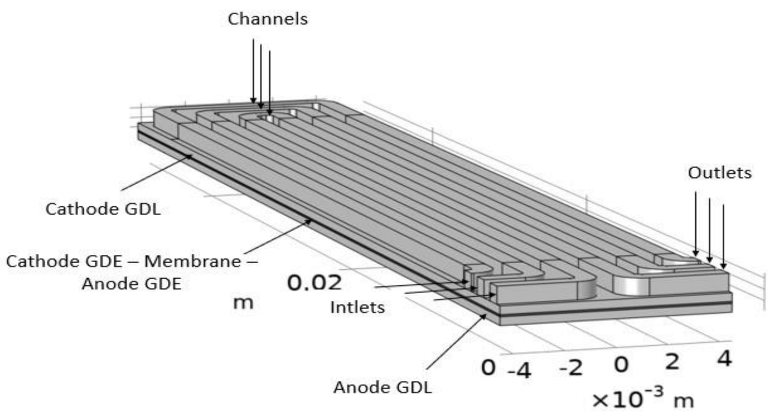


Fig. 1. Model geometry with three pass serpentine flow channels

Table 1
Design parameters

Description	Value
Number of channels	3
Rib width W_rib	7 e-4 m
Channel width W_ch	8 e-4 m
Channel height H_ch	8 e-4 m
Gdl height H_gdl	3.8 e-4 m
Membrane thickness H_mem	1 e-4 m
Plate width W_plate	0.05 m
Channel-to-channel distance	0.0015 m
Inner radius of channel corners r_ch	2.5 e-4 m

2.2 Basic Assumptions

In the model, the following assumptions were employed:

i. 3D domain
ii. Cell temperature is held constant
iii. Laminar flow due to small pressure
iv. Membrane is impermeable to reactant species
v. Ideal gas behavior is assumed for all gases.
vi. Gas diffusion layer exhibits isotropic and homogeneous properties
vii. Stationary model

2.3 Governing Equations

The governing equations can be written as follows [28, 29]:

Continuity equation:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=\frac{\partial \rho}{\partial t} \tag{1}$$

Where u, v, and w are the velocities in the x, y and z directions respectively, and ρ is the density of reactant gases.
Momentum conservation:

$$u\frac{\partial(\rho u)}{\partial x}+v\frac{\partial(\rho u)}{\partial y}+w\frac{\partial(\rho u)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)+S_{mom,x} \tag{2}$$

Where p, μ, and S_{mom} are the pressure, viscosity, and momentum sink terms respectively. The equations for the y and z directions are the same.

Species transport equation:

$$u\frac{\partial(\rho y_i)}{\partial x}+v\frac{\partial(\rho y_i)}{\partial y}+w\frac{\partial(\rho y_i)}{\partial z}=\frac{\partial(j_{x,i})}{\partial x}+\frac{\partial(j_{y,i})}{\partial y}+\frac{\partial(j_{z,i})}{\partial z}+S_i \tag{3}$$

Where Y_i is the mass fraction of each species i, S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources and $j_{x,i}$, $j_{y,i}$ and $j_{z,i}$ are the diffusion flux of species i in the x, y and y directions, respectively.

Charge conservation:

$$\nabla.(\sigma_{sol}\nabla\phi_{sol})+S_{sol}=0 \tag{4}$$

$$\nabla.(\sigma_{mem}\nabla\phi_{mem})+S_{mem}=0 \tag{5}$$

Where σ_{sol} and σ_{mem} are the electrical conductivities of the electrode and the membrane respectively, ϕ_{sol} and ϕ_{mem} are the phase potential of the electrode and the membrane respectively, S_{sol} and S_{mem} are the current source term of the electrode and the membrane.

2.4 Boundary Conditions

Several boundary conditions govern the model developed in this study. They include O_2 inlet and O_2 outlet which are the boundaries in the inlet and in the outlet, respectively. While slip wall conditions are applied to the GDL walls, no slip wall conditions are applied to the channel walls. On the anode side, the gas stream is assumed to be unaffected by the electrode reactions in the cell, consisting of 100% hydrogen within the entire cathode GDL and the gas diffusion electrode. The anode current collector boundary is connected to the ground, whereas a specific cell potential is applied to the cathode current collector boundaries.

3. Numerical Procedure

The model geometry is meshed with a free triangular on the lower anode GDL boundary and a free tetrahedral on the extremities of the channels and a swept mesh on the middle of channels, cathode GDL, membrane and anode GDL by COMSOL Multiphysics software (see Figure 2). There are 2785 edge elements, 22057 boundary elements, and 108723 domain elements in the complete mesh. The governing equations were solved using COMSOL boundary conditions by employing a simple algorithm based on the finite element method. The channel-to-channel cross flow is resolved by a finer mesh in the bottom channel and the GDL region located between the bottom channel's serpentine curve. The model was operated at a constant temperature of 453.15 K and cell voltage of 1 V. The physicochemical parameters used in this model are listed in Table 2.

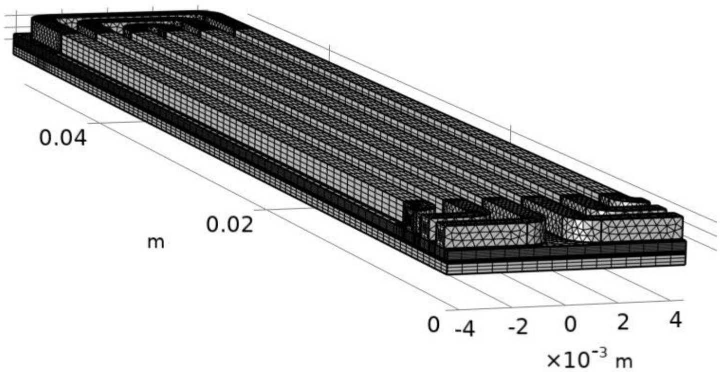


Fig. 2. Structure after meshing

Table 2
Physicochemical parameters

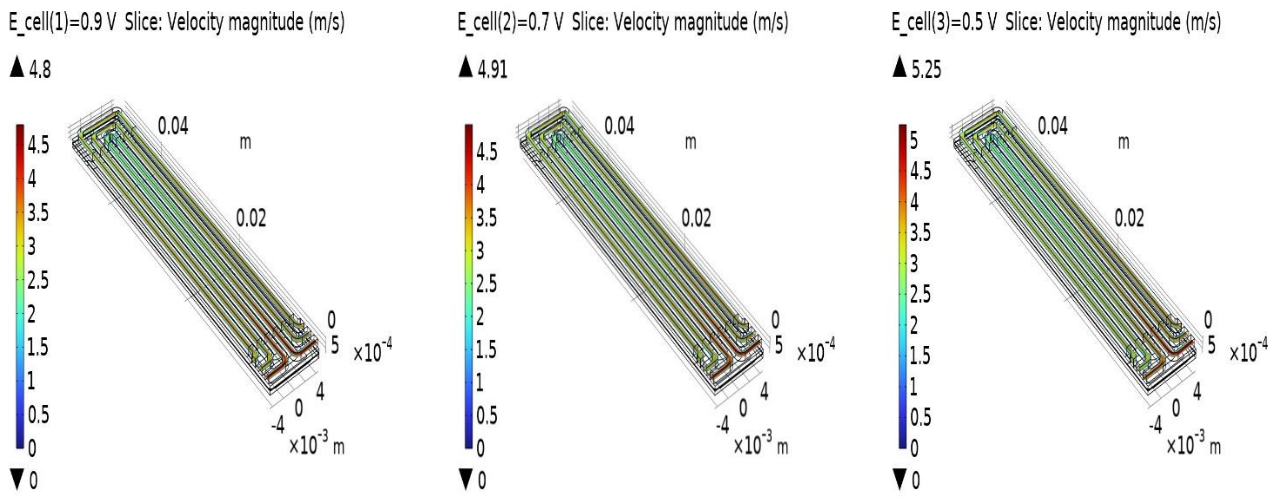
Parameter	Value
Cell temperature	453.15K
GDL porosity	0.4
GDL permeability	1.18e-11m^2
Inlet velocity	2 m/s
Electrolyte conductivity	9.825 S/m
GDL electronic conductivity	222 S/m
Humidification temperature of inlet gases	301.15K
Electrode thickness	5e-5m
Reference exchange current density, hydrogen oxidation	100 A/m^2
Reference exchange current density, oxygen reduction	0.001 A/m^2
Specific surface area	1e7 1/m
Anodic transfer coefficient, oxygen reduction	3
Anodic transfer coefficient, hydrogen oxidation	0.5
Cell voltage (varied in auxiliary sweep)	1 V

4. Results and Discussions

An examination of the PEMFC performance with 3-pass serpentine flow channels across varying operating voltages (0.9 V, 0.7 V and 0.5 V) was conducted using COMSOL Multiphysics software. Key parameters, including channels velocity distribution, oxygen mole fraction, pressure distribution and electrolyte current density along the z-axis at the cathode of the 3-passes serpentine flow fields PEMFC, are illustrated in Figures 3-6.

4.1 Channels Velocity Distribution

In Figure 3, the velocity distribution within the channels of the three-pass serpentine flow field model is illustrated under varying cell voltages. It is found that the velocity distribution within the channels exhibits similar trends for the three voltage values. Indeed, the highest velocity is observed at the midpoint of the channels, indicating efficient flow dynamics. Conversely, within the gas diffusion layer, the velocities tend to be lower. Furthermore, the upper end of the downward-most channels exhibits the lowest channel velocities. Among these three cell voltages, PEMFC operating at 0.5 V gives the maximum channels velocity distribution (5.25 m/s).

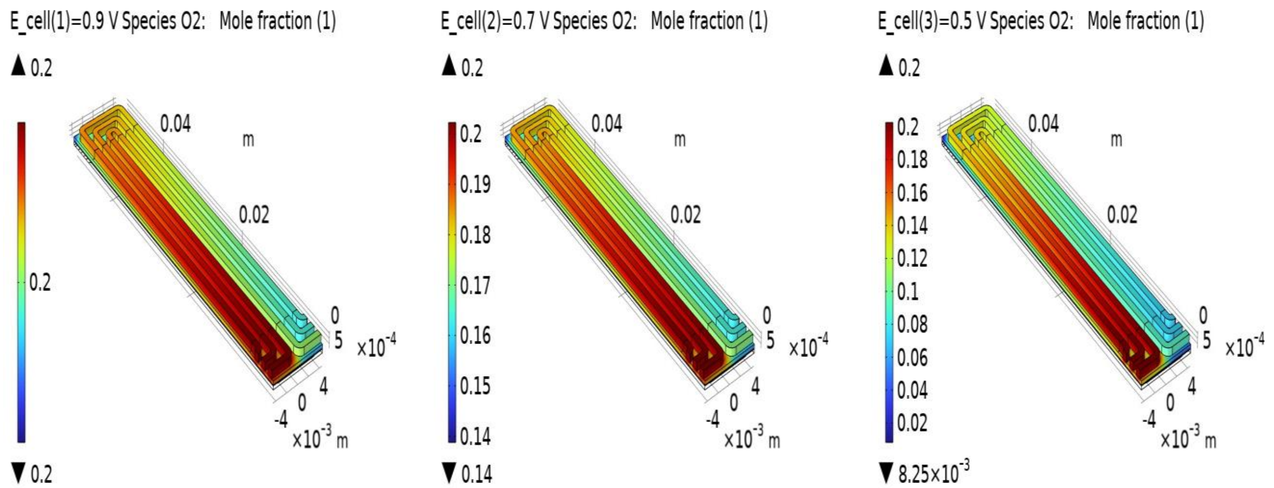


(a) (b) (c)

Fig. 3. Channels velocity distribution at (a) 0.9 V, (b) 0.7 V and (c) 0.5 V

4.2 Oxygen Mole Fraction

Figure 4 illustrates the distribution of the molar fraction of oxygen within the gas stream at different cell voltages. At 0.9 V, the oxygen concentration remains relatively uniform along the flow path. As the cell voltage decreases to 0.7 V and further to 0.5 V, a noticeable shift in the oxygen distribution becomes evident. The molar fraction of oxygen progressively decreases towards the outlet in both scenarios 0.7 V and 0.5 V. However, lower levels of oxygen are observed at the lower operating voltage of 0.5 V, indicating a more significant consumption of oxygen within the fuel cell.

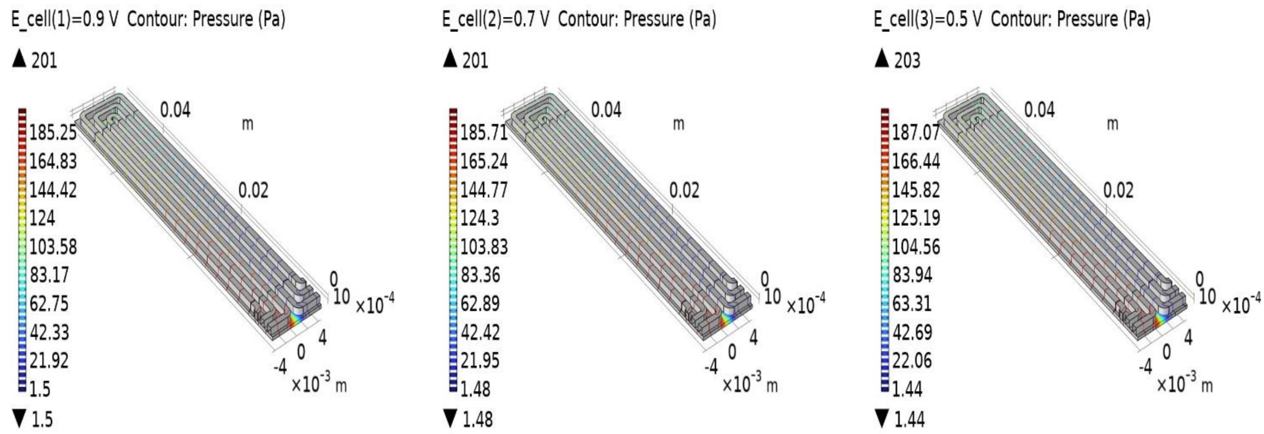


(a) (b) (c)

Fig. 4. Oxygen mole fraction at (a) 0.9 V, (b) 0.7 V and (c) 0.5 V

4.3 Pressure Distribution

Figure 5 illustrates the pressure distribution across the three-pass serpentine flow field model, operating at different cell voltages. A significance pressure difference is observed between the upward and downward flow sections of the lower channel. Among the three cell voltages, PEMFC operating at 0.5 V gives the maximum pressure distribution (203 Pa). This observation provides valuable insights into the dynamic response of the fuel cell under different operating conditions, emphasizing the importance of voltage variation in influencing pressure dynamics within the system.

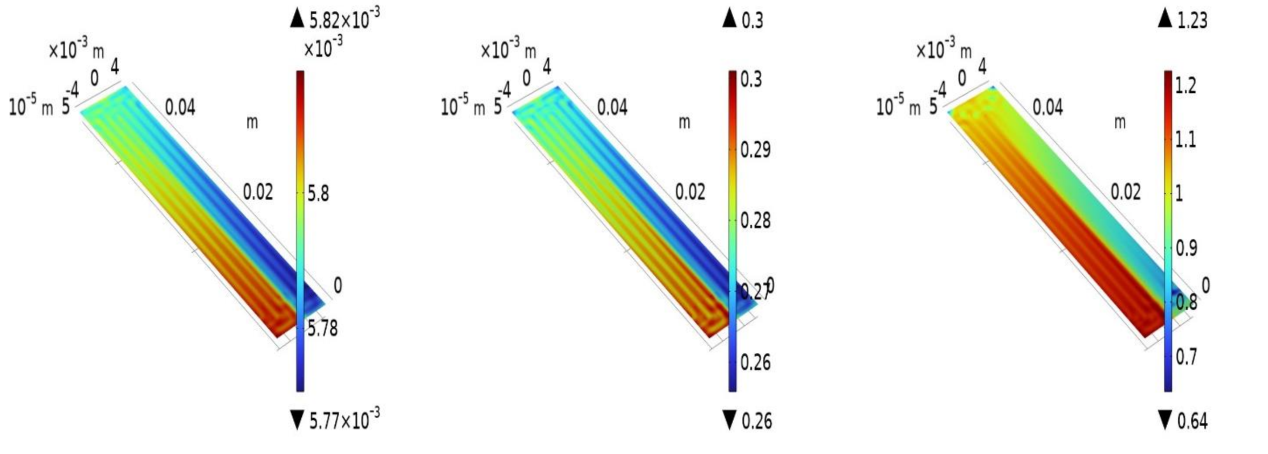


(a) (b) (c)

Fig. 5. Pressure distribution at (a) 0.9 V, (b) 0.7 V and (c) 0.5 V

4.4 Electrolyte Current Density

Figure 6 illustrates the electrolyte current density along the z-axis at the cathode for different cell voltages. It is known that the current density distribution is related to varying levels of oxygen molar fraction. It is therefore evident that regions less accessible to oxygen exhibit lower current densities. At 0.5 V, the current densities are generally higher, and less uniform distribution. This variation is attributed to factors such as the reduced oxygen concentration levels, as depicted in Figure 4. As we move towards the outlet, there is a decrease in current densities (blue color), which aligns with the lower oxygen levels observed.



(a) (b) (c)

Fig. 6. Electrolyte current density at the cathode in the z direction at (a) 0.9 V, (b) 0.7 V and (c) 0.5 V

5. Conclusion

In conclusion, an investigation using COMSOL Multiphysics software was conducted to analyze the impact of three-pass serpentine flow channels on the PEMFC performance across varying operating voltages (0.9 V, 0.7 V and 0.5 V). Several parameters effects were studied, including channels velocity distribution, oxygen mole fraction, pressure distribution and electrolyte current density along the z-axis at the cathode. It is found that the channels velocity distribution, pressure distribution and electrolyte current density were maximum operating at 0.5 V compared with other cell voltages. Furthermore, at an operating voltage of 0.5 V, a significant decrease in oxygen levels is observed, indicating increased oxygen consumption in the PEMFC. This research can contribute to understanding of the interplay between serpentine flow fields and cell voltages, offering crucial insights for enhancing the efficiency and operation of PEM fuel cells in practical applications.

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