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CFD ANALYSIS OF PRESSURE DROP REDUCTION IN PEMFC FLOW CHANNELS WITH DISTINCT CROSS-SECTION SHAPES

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Abstract: Proton exchange membrane fuel cells (PEMFCs) have great potential to produce renewable, sustainable and clean energy and reduce air pollutants to mitigate climate change. PEMFCs consist of distinct parts including anode and cathode bipolar plates having flow channels, gas diffusion layers, catalyst layers, and membrane. The flow channel geometry influences the flow and pressure drop characteristics of the channel and cell performance. In this work, a three-dimensional (3D) CFD model is built employing SOLIDWORKS and ANSYS Workbench. The innovative configurations are generated by changing the half of 0.2 x 0.2 mm square channel to 0.3 x 0.1 mm, 0.3 x 0.15 mm, 0.3 x 0.2 mm and 0.3 x 0.25 mm rectangular section at the top. The results showed that increasing rectangular section height significantly reduced pressure drop at the anode and cathode with a slight decrease in the current density at 0.4 and 0.6 V. The new configuration with 0.2 x 0.1 mm half square section at the bottom and 0.3 x 0.25 mm rectangular section at the top decreases the current density, anode and cathode pressure drop of 11%, 69% and 58%, respectively in comparison to 0.2 x 0.2 mm flow channel at 0.4 V. Taking into account pressure loss along the flow channels, this configuration is a good option to improve the cell performance.

Keywords: PEMFC, CFD, Cross-sectional geometry, Current density, Pressure drop

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1. Introduction

Fossil fuels like coal, natural gas and oil are the primary energy sources for the power production. But they are finite resources and burning of these fuels results in residual emissions which have the worst impact on the environment and our health. Therefore, researchers have been improving new technologies on producing alternative power sources. Fuel cells are the promising power sources because they are high power and quiet energy converters which transform the fuel chemical energy to clean electricity (Barbir, 2013). The PEM fuel cells (PEMFCs) have key advantages in comparison to other types of fuel cells thanks to low operating temperature, high energy density and having a wide power range (Wu, 2016). These advantages make PEMFC systems more suitable for distinct applications such as transportation, portable and backup power applications (Spiegel, 2008).

A PEMFC is a multi-part device comprises bipolar plates with gas channels and a membrane electrode assembly (MEA) containing a membrane, gas diffusion layers (GDLs), catalyst layers (CLs) at anode and cathode (Xing et al., 2019). The bipolar plate distributes hydrogen and oxygen along the channel. Hydrogen molecules are split into electrons and protons at the anode CL. Protons travel to the membrane whereas electrons move toward the cathode current collector by the electrical circuit. The electricity, water and waste heat are produced by combining electrons with protons and oxygen molecules at the cathode CL.

The flow channels play a pivotal role in the enhancement of the cell performance. Their shapes affect the distributions of gas species at the reacting area. That is, the channel geometry determines the reactant supply to anode and cathode CL where the electrochemical reactions occur. Besides the geometrical alteration of the channels also impacts pressure drop throughout the channel.

Researchers have scrutinized the impacts of the geometric modification of the channel on the efficiency improvement of PEMFC. Cooper et al. (2017) examined the impact of the length-to-width ratio of channels with interdigitated flow fields on augmenting the PEMFC performance. It was observed that decreasing the aspect ratio (the channel length to width ratio) by reducing the channel length resulted in higher overall performance. Chowdhury et al. (2018) demonstrated that both channel and land widths were equally crucial to increase the current density and the flow channels having 1 mm channel and land widths could be best choice regarding pressure drop and current density in the channel. Carcadea et al. (2021) inspected the influence of the serpentine channel numbers (7, 11, and 14) and cross-sectional size on performance of PEMFC with a large active area. Their results illustrated that a rise in number of serpentine channels or a decrease in the channel width to land width improved the cell performance, particularly at high current density. Kaplan (2021) scrutinized 15 case studies gained by altering the width and depth of the flow channel (0.2-1.6 mm) for 1 mm fixed depth and width. The results demonstrated that current density and velocity in the flow channel enhanced with reducing depth and width of the channel compared to base case having the channel cross-section of 1 x 1 mm (channel width x depth) at the cost of high pressure loss.

Brakni et al. (2024) assessed the impact of distinct flow field channels with constriction and widening sections at the middle of the channel on the PEMFC performance. They found that the configuration with a constricting hydraulic diameter of 50% showed better performance owing to this configuration enhancing fluid velocity and thus velocity distribution became more uniform at the disadvantage of higher pressure loss. Dong et al. (2023) improved a three-dimensional (3D) model to study the mass transport features and performance of the cell with novel two-block structures inside the channel at the cathode. Their findings revealed that the novel two-block structures augmented oxygen concentration thanks to convection influence of these structures and thus enhanced PEMFC performance with a slight increase in pressure drop.

The aim of the present study is to securitize the effect of the distinct flow channel cross-section shapes on the pressure drop in the flow channels and PEMFC performance. Previous research works were limited by the flow channels with square, rectangular, trapezoidal and stepped cross sections (Paulino et al., 2017). The present study describes the innovative channels with compound cross-section consisting of rectangular channels with a fixed cross-section (0.2 x 0.1 mm) at the bottom and larger cross-section at the top. Impact of this specific combination of cross-sections on current density, pressure, water and oxygen mass fraction distributions has not been addressed before.

2. Materials and Methods

In this work, a 3D geometric model is constructed employing SOLIDWORKS software and the structured mesh is generated using Sweep Method in ANSYS Meshing in Figure 1.

The model in Figure 1 consists of a membrane, anode and cathode current collectors, flow channels, GDLs and CLs. These parts are required for simulation of PEMFC using the Fuel Cell module (ANSYS Inc., 2018). Flow channel configurations with distinct cross-sections are obtained by fixing a half cross-section of 0.2 x 0.2 mm flow channel studied in previous published paper (Kaplan, 2023a) at the bottom combining with rectangular sections (0.3 x 0.1 mm, 0.3 x 0.15 mm, 0.3 x 0.2 mm and 0.3 x 0.25 mm) at the top in Figure 2.

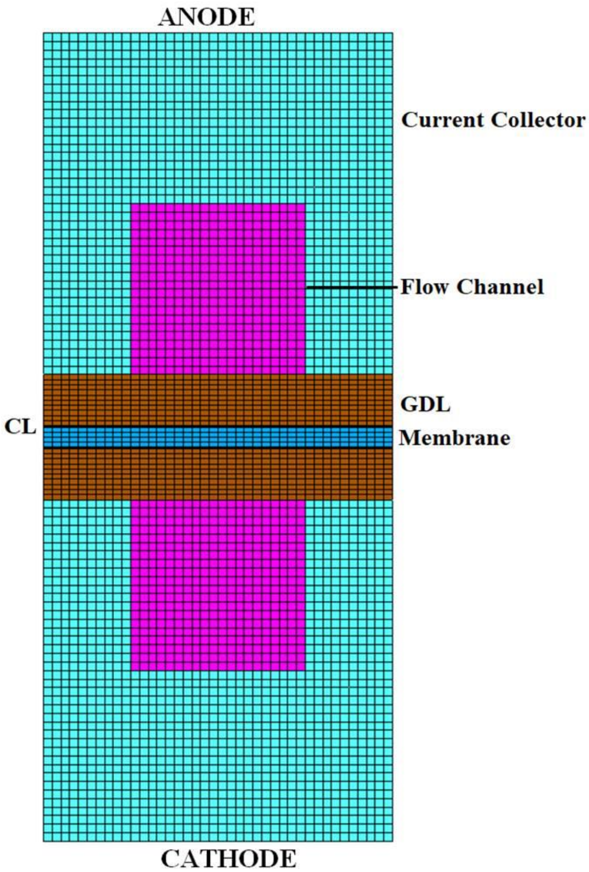

Figure 1. Grid structure and parts of PEMFC model.

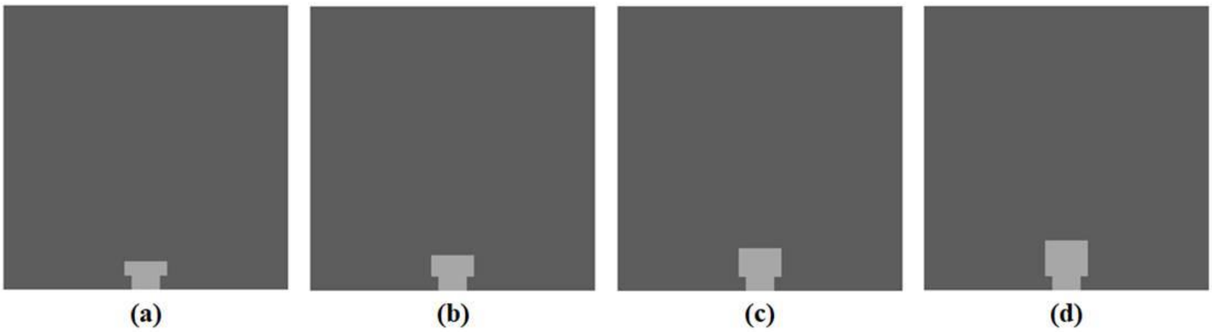

Figure 2. Configurations having a fixed half square section (0.2 x 0.1 mm) with rectangular sections: a) 0.3 x 0.1 mm, b) 0.3 x 0.15 mm, c) 0.3 x 0.2 mm and d) 0.3 x 0.25 mm.

The geometrical characteristics of the model utilized in the CFD analysis in Table 1 are based on Wang et al.'s experiment (2003).

The parameters and operating conditions employed in the CFD analysis are listed in Table 2.

The flow is considered steady state, incompressible and laminar. It is regarded that gas species behave like perfect gases. The MEA is supposed to be isotropic and homogenous porous media (Kaplan, 2023b).

The governing equations utilized in the PEMFC model are listed in Table 3.

Table 1. The geometrical features of the model

Parameter	Value
Cell length	70 mm
Cell width	2 mm
Channel height	1 mm
Channel width	1 mm
GDL thickness	300 μm
CL thickness	12.9 μm
Membrane thickness	108 μm

Table 2. Features and operating conditions used in the 3D CFD simulation

Parameter	Value
GDL and CL porosity (Kahveci and Taymaz, 2018)	0.5
GDL and CL viscous resistance (Kahveci and Taymaz, 2018)	1 x 10^{12} 1/m^2
CL surface/volume ratio	200000 1/m
Anodic and cathodic transfer coefficient at anode and cathode (Wang et al., 2003)	0.5 and 2
Reference exchange current density (anode and cathode)	4000 and 0.1 A/m^2
Anode inlet H_2 and H_2O mass fraction (Kaplan, 2022b)	0.2 and 0.8
Cathode inlet O_2 and H_2O mass fraction (Kaplan, 2022b)	0.2 and 0.1
Anode inlet mass flow rate (Kaplan, 2022a)	5.40 x 10^{-6} kg/s
Cathode inlet mass flow rate (Kaplan, 2022a)	3.29 x 10^{-5} kg/s
H_2O and H_2 reference diffusivity (Biyikoglu and Alpat, 2011)	7.33 x 10^{-5} m^2/s
O_2 and other species reference diffusivity	2.13 x 10^{-5} and 4.9 x 10^{-5} m^2/s
Open-circuit cell voltage	0.94 V
The cell temperature	343 K

Table 3. The governing equations used in the PEMFC model

Equations	Mathematical expressions
Continuity	$\nabla(\rho\vec{u})=0$
Momentum	$\frac{1}{(\varepsilon)^2}\nabla(\rho\vec{u}\vec{u})=-\nabla P+\nabla(\tau)+S_m$
Energy	$\nabla(\rho c_p\vec{u}T)=\nabla(k^{eff}\nabla T)+S_e$
Species	$\nabla(\vec{u}C_i)=\nabla(D_i^{eff}\nabla C_i)+S_i$
Charge	$\nabla\left(\sigma_{mem}\nabla\phi_{mem}\right)+R_{mem}=0,\ \nabla\left(\sigma_{sol}\nabla\phi_{sol}\right)+R_{sol}=0$

SIMPLE algorithm is utilized for a pressure velocity coupling in ANSYS Fluent. The gradient is computed by specifying Least Squares cell-based method. Second-order spatial discretization method is selected for pressure whereas the discretization scheme is second-order upwinding for momentum, density, energy and gases. The convergence criterion is set as 10^{-4} for the equations.

The fixed mass flow rates whose values given in Table 2 are specified the flow channel inlets at the anode and cathode. Atmospheric pressure is assigned for the flow channel outlet at the anode and cathode. All other faces are wall boundary conditions. Top faces of anode and cathode current collectors are determined as terminals. The potentials of anode and cathode terminals of 0 V and 0.39-0.92 V are selected respectively to verify the CFD model.

3. Results and Discussion

The PEMFC CFD model is validated using the current density measurements gained by Wang et al. (2003) in Figure 3.

As illustrated in Figure 3, the predicted results obtained by the PEMFC model are a well agreement with experiment, especially at lower and medium current densities whereas the model overprediction is found at higher current densities. This is probably due to the current model not regarding water (liquid) presence in the porous layers which causes a decrease in the porosity of the layers and augments species mass transfer resistance.

Figure 4 shows the estimated current densities for the configurations having a constant half square section (0.2 x 0.1 mm) at the bottom combining with different rectangular sections (0.3 x 0.1 mm, 0.3 x 0.15 mm, 0.3 x 0.2 mm and 0.3 x 0.25 mm) at the top for 0.4 and 0.6 V.

Figure 4 indicates that the current density slightly decreases with an increase of the height of rectangular section combining with a fixed half square section at the bottom for 0.4 and 0.6. It can be owing to the new configurations having higher land area near the GDLs in Figure 2 which contributes to minimize ohmic loses by reducing contact resistance between GDLs and bipolar plates. It is found that the land width is more sensitive than the rectangular section height for enhancing current density. The narrow channel with higher land width provided a higher cell current density (Chowdhury et al., 2018). Therefore, the maximum current density of 2.82 A/cm^2 are gained with the configuration with 0.1 mm rectangular section height compared to a 0.2 x 0.2 square channel with current density of 2.92 A/cm^2.

Figure 5 illustrates the oxygen mass fraction contours in the cathode flow channel, GDL and CL at the middle of the cell length for configurations having a constant half square section with rectangular sections of 0.3 x 01 mm and 0.3 x 0.25 mm for 0.4 V.

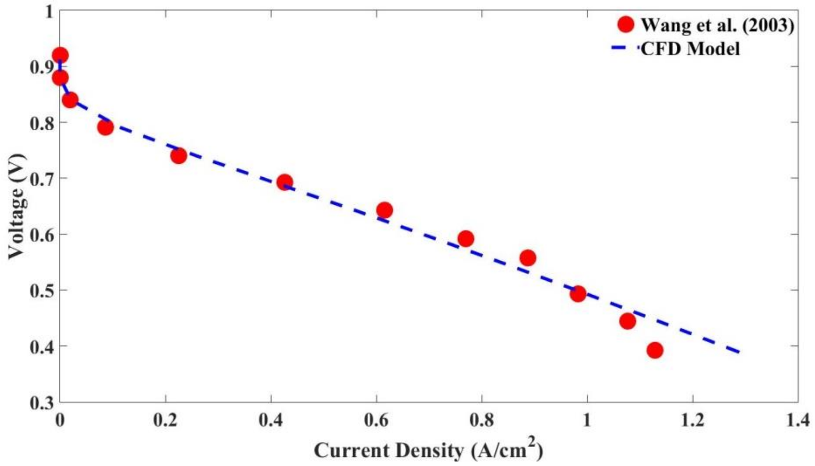

Figure 3. Validation of the PEMFC model with the measured data (Wang et al., 2003).

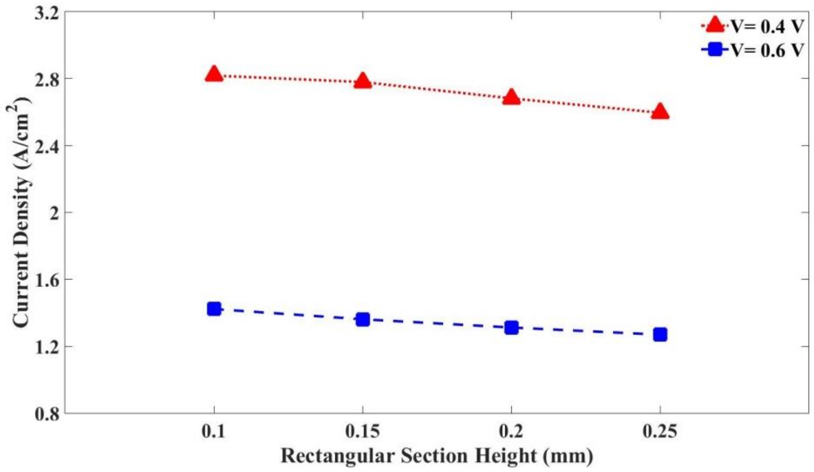

Figure 4. Change of current density as a function of height of a rectangular section at the top for 0.4 and 0.6 V.

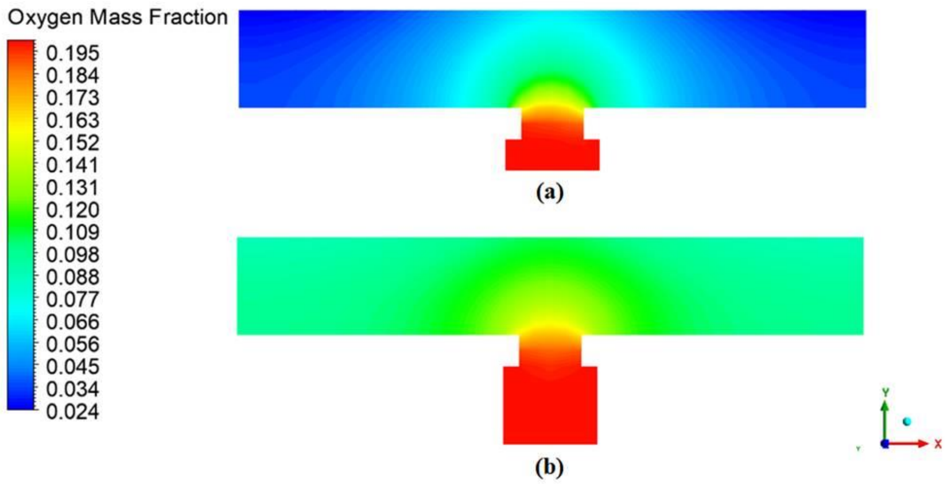

Figure 5. Contours of oxygen mass fraction in the cathode flow channel, GDL and CL at the midpoint of the cell length for channel configurations having a half square section with rectangular sections of (b) 0.3 x 0.1 mm and (c) 0.3 x 0.25 mm.

It is clear in Figure 5 that increasing the rectangular section height from 0.1 mm to 0.25 mm decreases consumption of oxygen in CL and GDL at 0.4 V. Since the channel with 0.1 mm rectangular section height produces higher current density in Figure 4, it consumes more oxygen for the reaction in the cathode CL as shown in Figure 5a compared to that having 0.25 mm rectangular section height in Figure 5b at 0.4 V.

Figure 6 demonstrates the water mass fraction contours in the cathode flow channel, GDL and CL at the middle of the cell length for configurations having a constant half square section with rectangular sections of 0.3 x 01 mm and 0.3 x 0.25 mm for 0.4 V.

It is apparent in Figure 6 that a rise in the rectangular section height from 0.1 mm to 0.25 mm reduces water production in CL and GDL at 0.4 V. 0.1 mm rectangular section height case generates more water in Figure 6a compared to the channel having 0.25 mm rectangular section height in Figure 6b owing to this configuration producing higher current density in Figure 4 at 0.4 V. sites. It is concluded that lower cross-sectional area results in a higher reaction rate and thus power density of the PEMFC.

Figure 7 illustrates the pressure contours at the cathode flow channel inlet and flow channel/GDL interface for configurations having a constant half square section with rectangular sections of 0.3 x 01 mm and 0.3 x 0.25 mm for 0.4 V.

It is seen that higher pressure distribution existed in the channel inlet section for both configurations shown in Figure 7a and 7b. The pressure diminishes gradually from the inlet towards the outlet because the gas mixture diffusion and frictional loss along the channel configurations. Larger rectangular section height in Figure 7b reduces pressure drop by decreasing friction. Chowdhury et al. (2018) provided similar results for flow channels having higher channel widths with a constant channel depth. Namely, pressure drop decreased with an increase in the flow channel size.

Table 4 indicates the current density and pressure drop results in the base (1 x 1 mm), square channel (0.2 x 0.2 mm) and innovative configurations having half square channel (0.2 x 0.1 mm) at the bottom with rectangular sections (0.3 x 0.1 mm, 0.3 x 0.15 mm, 0.3 x 0.2 mm and 0.3 x 0.25 mm) at the top for 0.4 V.

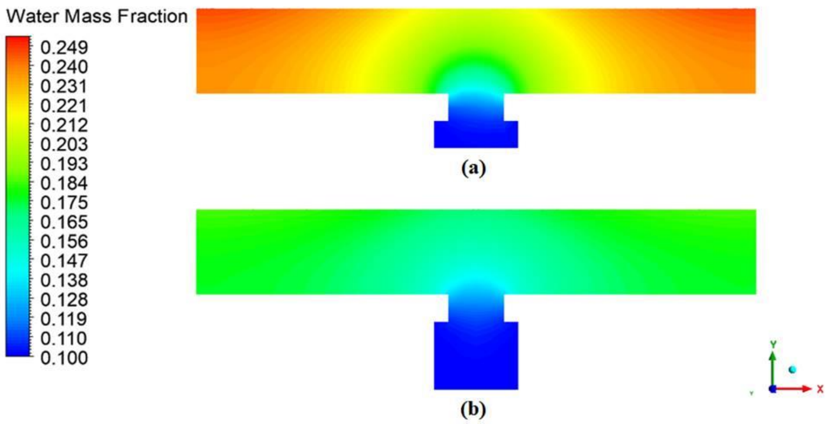

Figure 6. Contours of water mass fraction in the cathode flow channel, GDL and CL at the midpoint of the cell length for channel configurations having a half square section with rectangular sections of (b) 0.3 x 0.1 mm and (c) 0.3 x 0.25 mm.

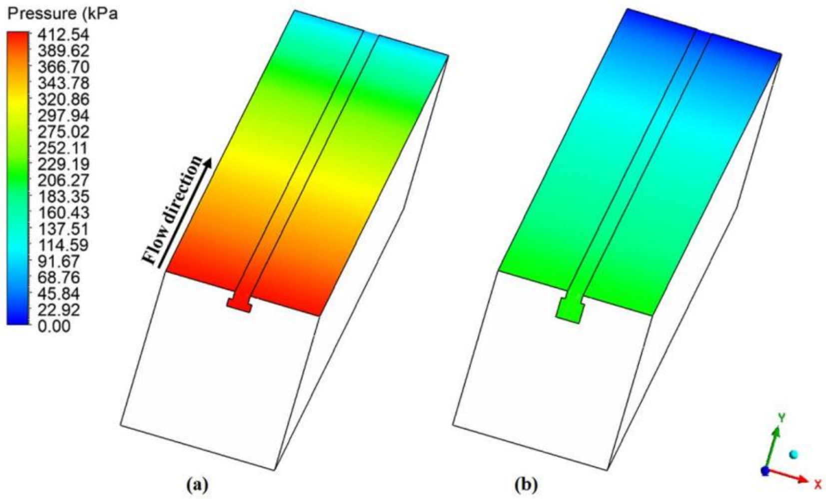

Figure 7. Contours of pressure at the cathode flow channel inlet and flow channel/GDL interface for channel configurations having a half square section with rectangular sections of (b) 0.3 x 0.1 mm and (c) 0.3 x 0.25 mm.

Table 4. Comparison of current density and pressure drop results for flow channel configurations (base, square and half square with different rectangular sections) for 0.4 V

Configurations	Current density (A/cm²)	Pressure Drop	
		Anode (kPa)	Cathode (kPa)
Base (1 x 1 mm)	1.26	0.73	2.45
Square (0.2 x 0.2 m)	2.92	163.11	511.68
Half square with rectangular (0.3x 0.1 mm)	2.82	130.46	412.54
Half square with rectangular (0.3x 0.15 mm)	2.78	90.22	322.79
Half square with rectangular (0.3x 0.2 mm)	2.68	65.52	257.88
Half square with rectangular (0.3x 0.25 mm)	2.60	49.96	212.59

It is obvious in Table 4 that new configurations generated by modifying half square section at the top remarkably reduces the anode and cathode pressure drop with a slight decrease in the current density compared to 0.2 x 0.2 mm square channel. Besides the pressure drop at the cathode is much higher than that at the anode. This may be because of a mixture of gases in the channel at cathode being more complicated compared to that at the anode. The maximum current density is achieved with the configuration with 0.2 x 0.2 mm cross section channel but the cathode channel of this configuration produces the highest pressure drop of 511.68 kPa in Table 4. Higher pressure drop leads to the extra pumping work and thus reducing the cell efficiency. The configuration having 0.2 x 0.1 mm half square section with 0.3 x 0.25 mm rectangular section reduces current density, anode and cathode pressure drop by 11%, 69% and 58%, respectively in comparison to 0.2 x 0.2 channel at 0.4 V. Regarding to pressure drop and current density in the channels, this configuration is better option to improve PEMFC performance.

4. Conclusion

In the present study, a 3-D numerical model is improved and validated by the measured data (Wang et al., 2003) to examine the effect of changing half section of square flow channel at the top to distinct rectangular sections on pressure drop and PEMFC performance. The main findings are as follow:

- 0.2 x 0.2 mm square channel leads to considerably higher current density and pressure drop at the anode and cathode at 0.4 and 0.6 V.
- Innovative configurations produced by altering dimensions of half of square channel at the top remarkably reduce pressure in the anode and cathode flow channel with not considerably decreasing the current density.
- New configurations provide the higher land width dimensions near the GDL contributing to reducing contact resistance between GDL and bipolar plate and thus minimizing ohmic loses.
- A rise in the height of rectangular section at the top leads to increasing oxygen concentration and decreases water concentration at 0.4 V.
- Considering current density and pressure drop, the new configuration with the half square section (0.2 x 0.1 mm) at the bottom and the rectangular section (0.3x 0.25 mm) at the top is more efficient option with 11%, 69% and 58% reduction of the current density, anode and cathode pressure drop compared to 0.2 x 0.2 flow channel at 0.4 V.

These outcomes emphasize the significance of the flow channel cross-section shapes in the design of efficient fuel cell systems. Future work including the impact of distinct operating conditions and material properties on the cell performance which would improve the innovative configurations suggested in this study.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	M.K.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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