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EFFECT OF VARIATION IN CHANNEL HEIGHT TO WIDTH RATIO FOR THE PERFORMANCE OF HT-PEM FUEL CELL

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Abstract: Channel's height-width ratio played a significant role on the HT-PEMFC's performance. In the current study, a rectangular parallel flow field design was used to analyze the three different ratios between the channel height-width to observe the various factors that includes velocity field vectors, pressure and water mass fraction in the anode and cathode compartments, membrane current density, the mass fraction of H2, N2 and O2, also polarization curve for HT-PEMFCs. In the first ratio 1:1 where the height and width of gas channel remains the same. By keeping the same channel's inlet-outlet area, the height in the second ratio (4:5) is smaller than the width, while the height in the third ratio (5:4) is larger. Using the COMSOL 6.0 Multiphysics software, we performed a numerical simulation modelling of the HT-PEMFC for this investigation. When channel height to width is kept at (1:1) shows good performance for polarization plot simulation results.

***Index Terms* - H: W ratio, PEMFCs, Mass fraction, Ohmic voltage drop, Polarization plot, Velocity.**

1 INTRODUCTION

A device that converts the chemical energy of hydrogen into electrical energy through an electrochemical reaction [1-3] is called a fuel cell, i.e., the oxidation reaction at the anode and reduction reaction at the cathode between the hydrogen and oxygen, in which hydrogen donates an electron to the anode through the oxidation reaction. A hydrogen ion (H^+) with fewer electrons is called a proton [4] and produces water or heat. Fuel cells, as durable can provide a long-term solution with minimal or no greenhouse gas emissions [5-8]. According to the electrolyte employed, fuel cells are categorized. A PEM fuel cell is made of three main components. A film of solid polymer saturated between two electrodes, the negatively charged electrode is called the anode and the positively charged electrode is called the cathode. A bipolar plate with numerous gas flow channels (GFC) and a catalyst layer (CL) make up the anode and cathode. The gas diffusion layer (GDL) with a microporous layer (MPL) is also present [9, 10]. The working block diagram of a PEMFC is shown in Fig. 1.

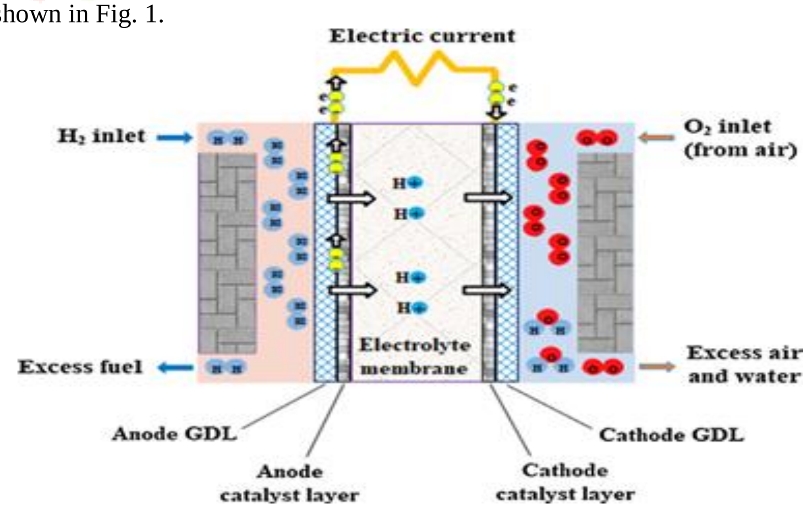


Fig. 1 – Working block diagram of PEMFC

PEM fuel cells supply hydrogen (H_2) on the anode side and air (O_2) on the cathode side. These two gases combine to generate chemical energy which is converted into electricity. However, due to the low energy conversion efficiency, part of the chemical energy is converted into waste heat instead of electricity [10, 11]. Hydrogen undergoes oxidation to form protons at the anode as shown below [12, 13].

$$2H_2 \rightarrow 4H^+ + 4\,e^- \qquad (1)$$

Energy is released this reaction. The oxygen reacts at the cathode with the electrons released from the electrodes and the proton (H^+) from the membrane. This leads to the formation of water (H_2O). Oxygen undergoes reduction from water at the cathode as given below [14].

$$O_2 + 4\,e^- + 4H^+ \rightarrow 2H_2O \qquad (2)$$

In the overall process, the hydrogen (H_2) fuel burns or proceeds in a simple reaction as follows [15-18].

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat} \qquad (3)$$

For automobile applications, PEMFCs are the most acceptable sources for energy converters [19-21] used in purely hybrid power supply systems and providing rated power to loads. The widespread application of PEMFCs is limited by their high economic cost, fuel availability, and durability, or the difficulty in maintaining proper temperature and water management, which greatly affects PEMFC performance [22, 23]. PEMFCs consider of two types, the first is low-temperature PEMFCs (LT-PEMFCs) and the second is high-temperature PEMFCs (HT-PEMFCs). In PEMFCs, HT-PEMFCs [24-28] are an alternative energy source that attracts much attention due to some unique criteria such as low thermal operating conditions, higher efficiency, shorter size, and simplicity of design [4]. Some attractive features of PEMFC systems include lightweight, maximum energy density, low pollutant emissions, and low operating temperature. The performance of HT - PEMFCs largely depends on the functional conditions like temperature, pressure, cell voltage, the inlet-outlet velocity of gases, humidity [29-31], designing parameters like channel length, height, width, rib width channel shape and size, membrane thickness, GDL and GDE thickness also, the transport phenomena in the cell [32, 33], the rate of electrochemical reaction [34], the mechanical design and the manufacturing process. They function at higher temperatures between 120 and 180 °C and produce a stable voltage under steady-state circumstances. Faster electrochemical kinetics, better water management, and carbon monoxide tolerance are all attributes of the HT-PEMFC.

Various scholars have out both numerical simulation and experimental work on HT-PEMFC. Jiang and Wang designed a two-phase flow model to investigate the production and transport of liquid water by fully coupling mass transport, heat transport, and electrochemical processes. The performance of the fuel cell is influenced by the concentration of liquid water in the cathode channels, which predominates the diffusion of liquid water inside the cell [35]. A multiphase model was created by Yuan et al. to predict the effect of working variables such as pressure, cell temperature, reagent gas relative humidity, and air stoichiometry on cell performance. The outcomes demonstrated that raising the temperature and operating pressure can enhance battery performance. Moreover, it has been found that the performance is better when the relative humidity of the air is moderate when the hydrogen is sufficiently humidified [36]. Kang et al. developed a multiphase porous cathode model for studying liquid water flooding in interdigital flow field designs. The results show that liquid water overflow occurs in this type of cathode design. Also, the liquid water flooding process consists of three stages. These are the porous layer stage, channel stage, and drainage stage. This model is only applicable to the cathode side and does not take into account heat transfer and electrochemical reactions [37]. Wang used a two-phase flow model assuming isothermal conditions to study multiphase flow, mass transport, and electrochemical processes and their interactions. The results show that two-phase flow is possible in anodic and cathodic scattering media and that the two phases coexist under low humidity conditions. The model does not take into account the phase changes of the water [22]. The main goal of this research is to investigate the impact of different ratios between the height and width of gas flow channel geometry on cell performance using COMSOL 6.0 Multiphysics software.

A. 3D CHANNEL STRUCTURE

The structure and shape of channels are generally blockish. Changing the shape of the channel can affect the accumulation of water in the fuel cell and the flow of fuel and oxidizer. The shape and size of the water driblets are determined by the hydrophobicity of the pervious medium and the walls of the channels. The confines of the channels are generally around 1 mm. In this study, we investigated three different ratios in the channel's height and width. These three ratios are as follows 1:1, 4:5, and 5:4. The simulations revealed that the optimal channel dimensions for PEMFCs were 1.0, 1.0, and 0.90932 mm for channel height, width, and rib range independently. These dimensions depend on the overall design and size of the fuel cell. Channel structure affect fuel and oxidizer flow rates, pressure drop, heat and water formulation, and power generated in a fuel cell. Wider channels allow for better fuel contact with the catalyst bed, have less pressure drop, and provide more efficient water removal. However, if the channel is too wide; it will not provide sufficient support for the MEA layer. Widening the spacing between the flow channels area reduces and exposed to reactants and promotes water accumulation [38].

II. DESCRIPTION OF THE MODEL

A simple isothermal 3D model designed to predict the performance of membrane-based PEMFCs. In this modeling, we have applied the following procedure. i.e., electrochemistry module < Hydrogen fuel cell < Proton exchange membrane and two times fluid flow module < Porous media & Subsurface flow < Free & Porous media flow for a first anode and secondary for cathode with reacting flow in Multiphysics.

A. MODEL ASSUMPTIONS

1. PEMFCs operate at a temperature above 150°C, and a pressure of approximately about 1 atm [39].
2. Water only exists in the form of vapor.
3. The resistivity of water from the anode to the cathode is assumed to be zero.
4. The proton transfer mechanism through the acidic medium (H_3PO_4) in the membrane.
5. The gaseous mixture is considered ideal gas.
6. Due to the low Reynolds number, the flow is considered laminar.
7. The GDL consists of an isotropic and homogeneous porous material.

B. MODEL**ING DOMAIN**

The 3D computational geometry of PEMFC includes a membrane section, cathode section, and anode section. cathode section and anode section are made of gas flow channels, gas diffusion layers (GDLs), or CL. Fig. 2 shows seven computational domains of this model.

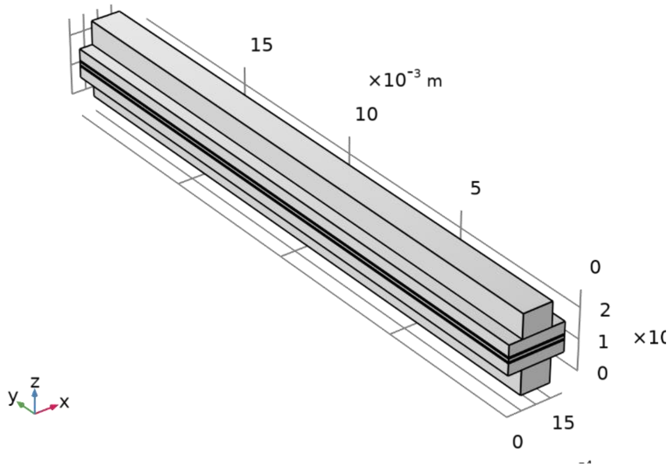


Fig. 2- PEMFC geometry created at COMSOL Multiphysics software

The Modeling statics of this study is given in Table 1.

S. No.	Description	Value
1	Space dimension	3
2	Number of domains	7
3	Number of boundaries	40
4	Number of edges	72
5	Number of vertices	40

C. USING GOVERNING EQUATIONS

Some governing equations and boundary conditions are used in this study. These governing equations and conditions are given below.

In electrolyte phase

$$\nabla \cdot i_l = i_{v \cdot total} \quad (4)$$

$$i_l = -\sigma_{l \cdot eff} \nabla \phi_l \quad (5)$$

In insulation condition

$$-n \cdot i_l = 0 \quad (6)$$

In the electronic conducting phase

$$\nabla \cdot i_s = -i_{v \cdot total} \quad (7)$$

The ionic charge

$$\nabla \cdot i_s = -\sigma_s \nabla \phi_s \quad (8)$$

$$-n \cdot i_s = 0 \quad (9)$$

Potential at anode current collector

$$\phi_s = 0 \quad (10)$$

Potential at cathode current collector

$$\phi_s = \phi_{s.bnd} \quad (11)$$

The parameters $D_{ik,eff}$ is defined

$$D_{ik,eff} = \epsilon_g 1.5 D_{ik} \quad (12)$$

The cell potential is given by

$$\eta = E_{ct} - E_{eq}, \quad E_{ct} = \phi_s - \phi_l \quad (13)$$

Continuity equation

$$\nabla . (\rho u a) = 0 \quad (14)$$

As the flow is laminar and due to two-phase flows calculate the Momentum species by using Darcy's Law.

$$\rho (u \cdot \nabla) u = \nabla \cdot [-\rho l + K] + F \quad (15)$$

Mass transfer to another phase

$$Q_m = \sum_i R_i \quad (16)$$

Stefan velocity

$$\rho u_s = n \cdot \sum_i (j_i + \rho u_s \omega_i n) \quad (17)$$

D. DESIGNING AND FUNCTIONAL PARAMETERS

The most crucial parameters in the designing or manufacturing and operating process to use in the fuel cell are called designing and functional parameters. Some designing parameters and functional variables of this study are given below in Table 2 and Table 3.

Table 2- Designing conditions of the HT-PEMFC.

S.No.	Condition Name	Condition Value
1	Cell length [39]	0.02 m
2	Width of rib	9.0932E-4 m
3	Width of GDL	3.8E-4 m
4	Thickness of Porous electrode [39]	5E-5 m
5	Thickness of membrane [39]	1E-4 m
6	Channel height	0.89mm, 0.8mm, 1mm
7	Width of Channel	0.89mm, 1mm, 0.8mm

Table 3- Functional variables for the HT- PEMFC.

S.No.	Variable Value	Variable Name
1	8.31 J/Kmol	Gas constant
2	0.4	GDL gas porosity [39]
3	0.3	Catalyst layer electrolyte volume fraction
4	0.3	Catalyst layer gas pore volume fraction
5	1.18E-11 m²	GDL permeability [40]
6	2.36E-12 m²	Catalyst layer permeability
7	222 S/m	GDL electric conductivity [39, 41]
8	9.825 S/m	Conductivity [42]
9	423.15 K	Cell temperature
10	1.0133E5 Pa	Reference pressure
11	0.95 V	Cell voltage
12	0.001 A/m²	Cathode reference exchange current density
13	100 A/m²	Anode reference exchange current density
14	1	Transfer coefficient, cathode [38]
15	1E7 1/m	Specific surface area
16	301.15 K	Humidification temperature
17	3781.4 Pa	Water partial pressure
18	0.037319	Inlet water molar fraction
19	0.96268	Inlet hydrogen molar fraction
20	0.20216	Inlet oxygen molar fraction
21	0.38186 A	Operating current for gas flow calculations
22	1.2	Anode stoichiometry
23	2.0	Cathode stoichiometry
24	2.6586E-10 m/s	Inlet velocity, anode
25	1.3188E-9 m/s	Inlet velocity, cathode

III. RESULTS AND DISCUSSIONS

Complete mesh statics of this study is given in Table 4 and Table 5 shows the relationship between the fuel cell voltage and current density.

Table 4- Mesh statics of this research

S. No.	Description	Value
1	Status	Complete mesh
2	Mesh vertices	21528
3	Hexahedra	18950
4	Quads	7166
5	Edge elements	952

6	Vertex elements	40 [43]
7	Number of elements	18950
8	Minimum element quality	0.9663
9	Average element quality	0.9922
10	Element volume ratio	0.028492
11	Mesh volume	6.482E-8 m^3

Table 5 – Comparison of the fuel cell current density at different voltage.

V_cell (V)	Current density (mA/cm^2), H: W (1:1)	Current density (mA/cm^2), H: W (4:5)	Current density (mA/cm^2 H: W (5:4)
0.95000	2.7811E-4	2.7792E-4	2.7803E-4
0.90000	0.0010271	0.0010248	0.0010261
0.85000	0.0033235	0.0033023	0.0033141
0.80000	0.0084748	0.0083700	0.0084259
0.70000	0.027667	0.027023	0.027313
0.60000	0.054155	0.052377	0.052938
0.50000	0.083381	0.079568	0.080016
0.40000	0.11056	0.11056	0.10188

A. POLARIZATION PLOT

The cell polarization curve draws between cell potential and current density. It is called cell IV characteristics. The present fuel cell model was validated by predicting IV curves for various channel height to width ratios. The predicted IV curves correlate closely with the experimental and previously simulated IV curves [22, 44], as illustrated in Fig. 3. This curve shows higher current density value (0.11056 mA/cm^2) for ratio height to width at 1:1, moderate (0.11056 mA/cm^2) for 4:5 and lowest (0.10188 mA/cm^2) for 5:4 at 0.4 voltage.

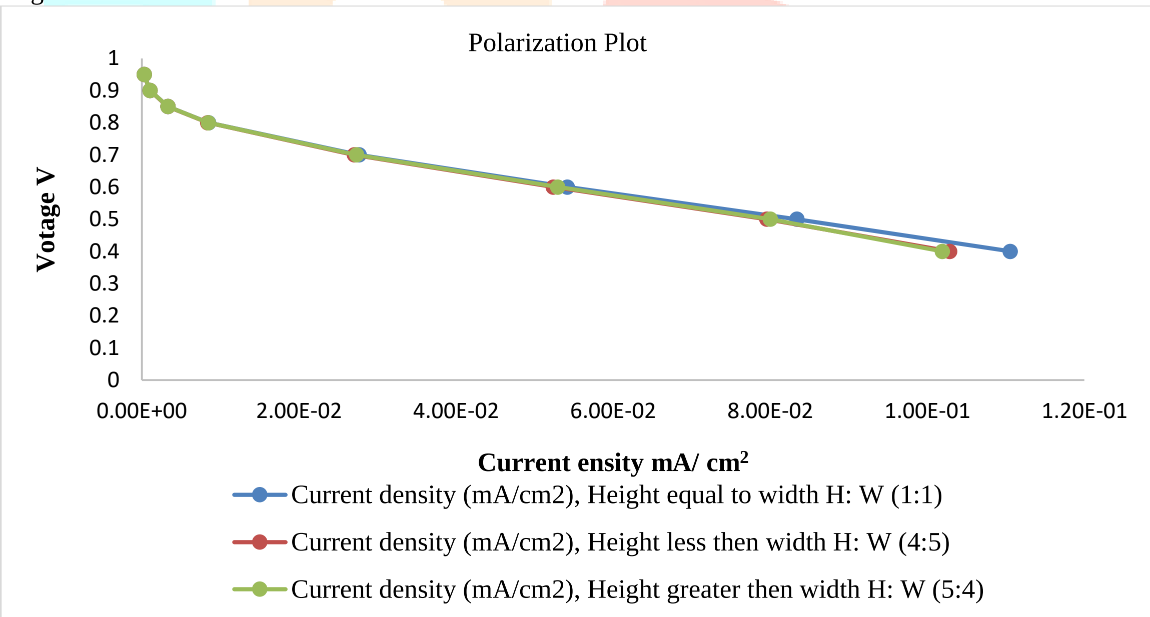
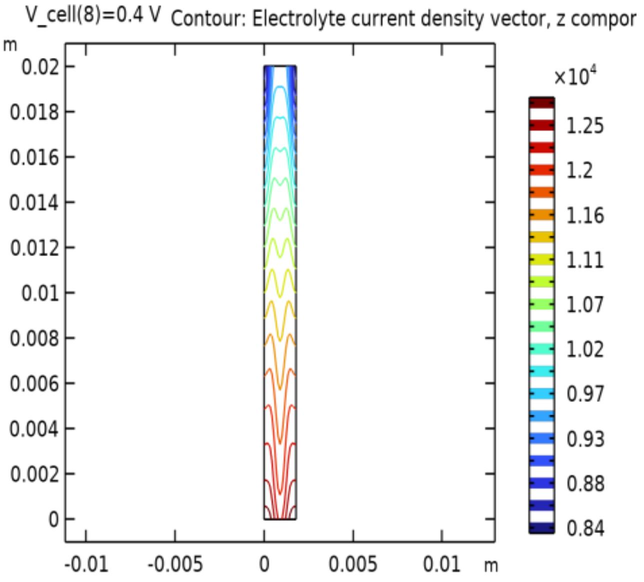


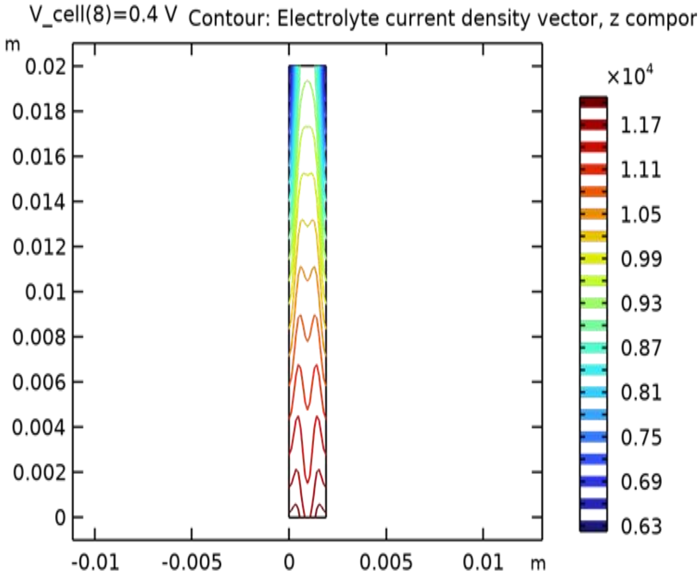
Fig. 3- HT-PEMFCs performance is characterized by its polarization curve under different designing conditions Height and width are equal (1:1) Height greater than the width (5:4) and Height less than width (4:5).

B. MEMBRANE CURRENT DENSITY

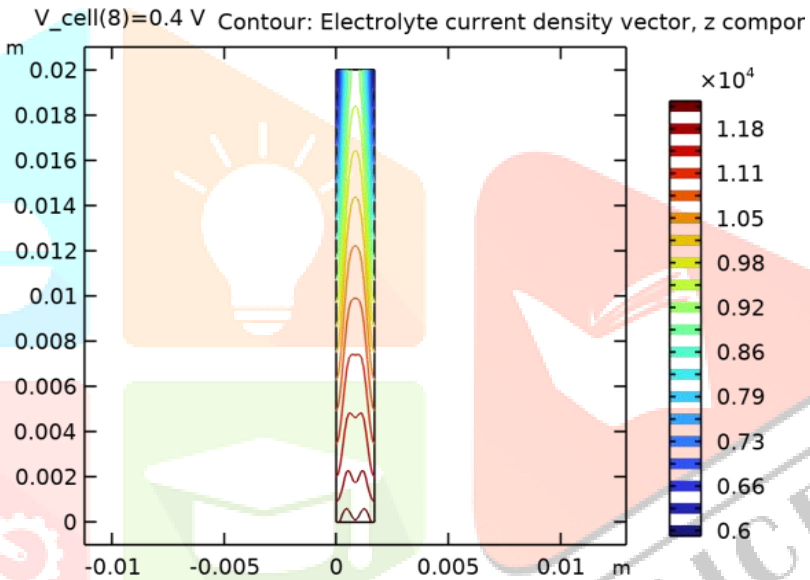
The membrane current density (ionic current density) is highest at 0.4 Voltage in the direction of the z-axis at the center of the membrane. In the direction of the y-axis, the current density is lower towards the output due to lower reactant concentration. In the x-axis direction, the current density is highest near the channel, where the reactant concentration is high, but decreases towards the center of the channel. This is due to the ohmic voltage drop in the GDL. The membrane current density of an HT-PEMFC is shown in Fig. 4.



(a) H: W (1:1)



(b) H: W (4: 5)

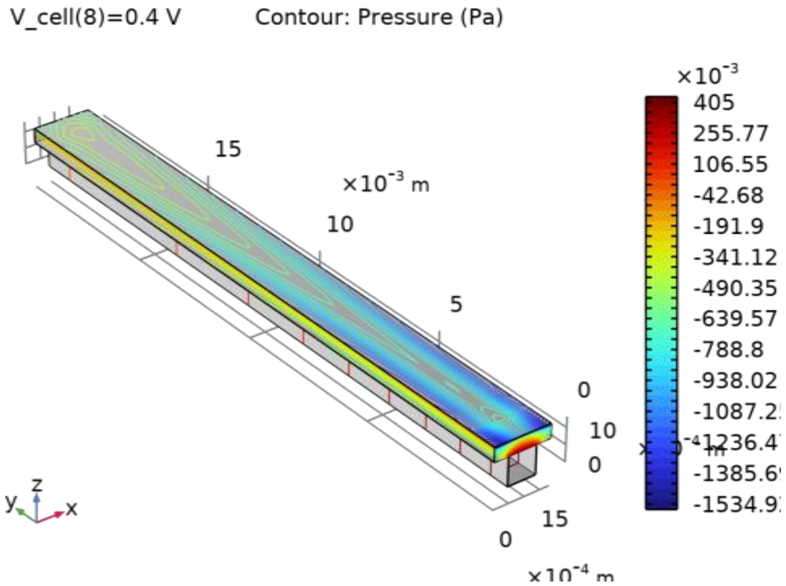


(c) H: W (5: 4)

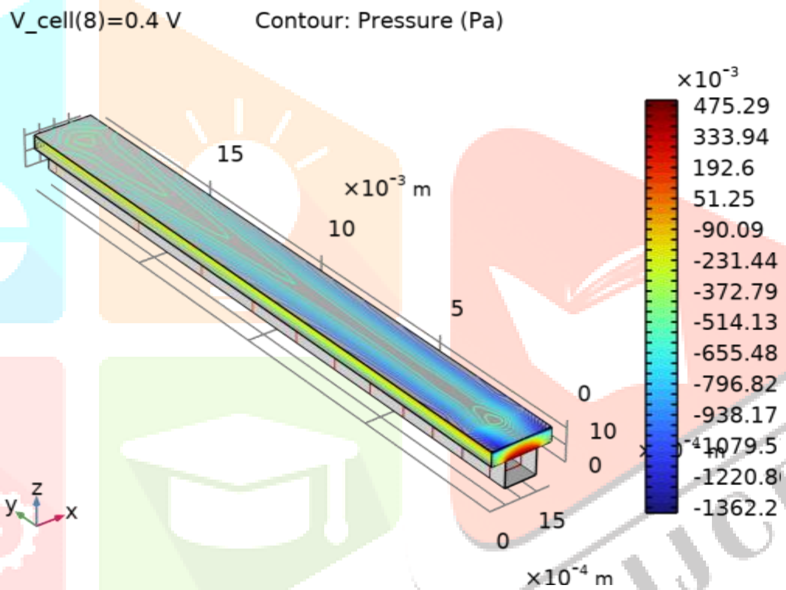
Fig. 4- Performance comparison of HT-PEMFC ionic current density under different designing conditions: (a) Height and width are equal (1:1) (b) Height greater than the width (5:4) (c) Height less than width (4:5).

C. PRESSURE PROFILE FOR ANODE

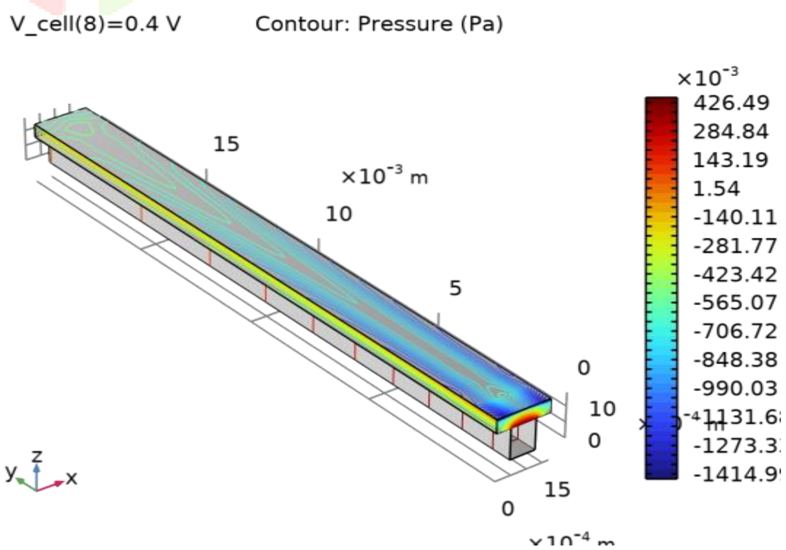
The pressure profile at the anode compartment for the same voltage level. The case channel height width ratio is 4:5. In this case the pressure profile at the anode compartment is high at the same voltage level. The pressure at the anode compartment is shown in fig. 5.



(a) H: W (1:1)



(b) H: W (4:5)

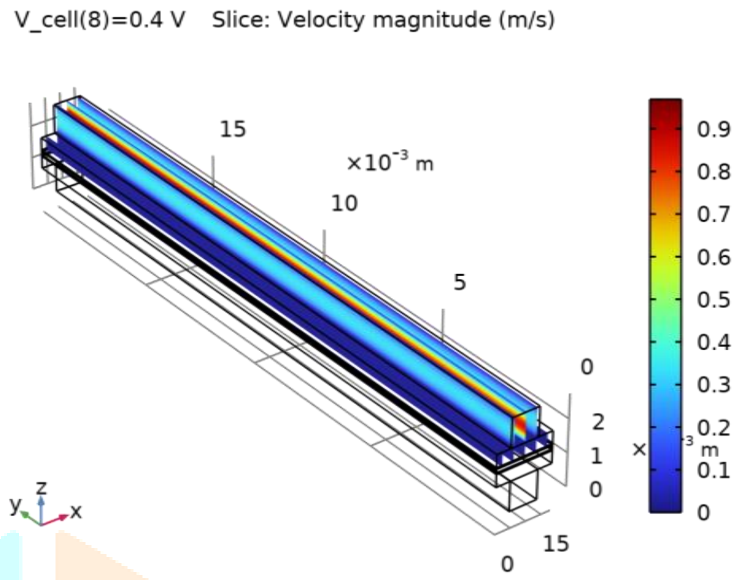


(c) H: W (5:4)

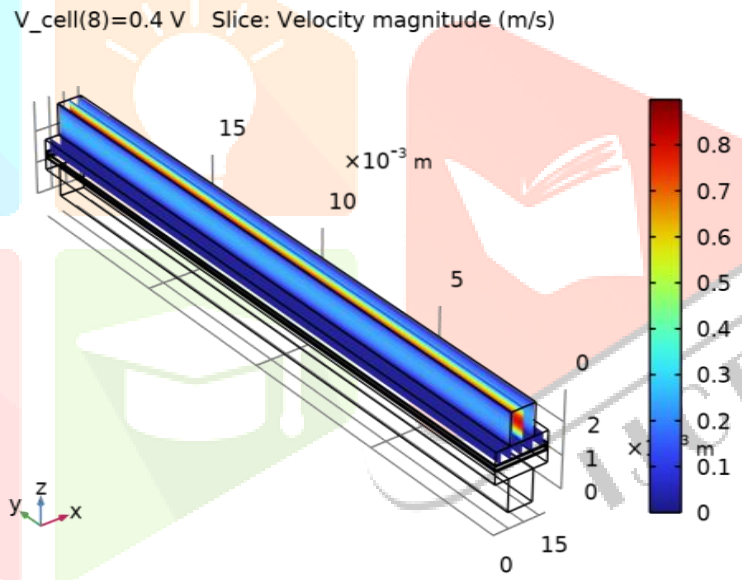
Fig. 5- Shows the pressure profile at the anode compartment under different designing conditions (a) Height and width are equal (1:1) (b) Height less than width (4:5) (c) Height greater than the width (5:4).

E. VELOCITY MAGNITUDE AT THE CATHODE

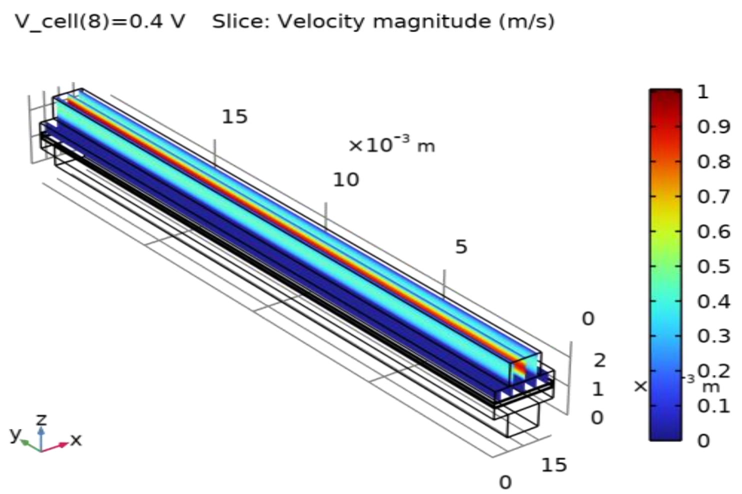
The velocity magnitude at the cathode compartment for the same voltage level. A case channel height and width ratio are 4:5, in this case, the velocity magnitude at the cathode compartment is high at the same voltage level. The velocity magnitude at the cathode compartment is shown in Fig. 6.



(a) H: W (1:1)



(b) H: W (4:5)

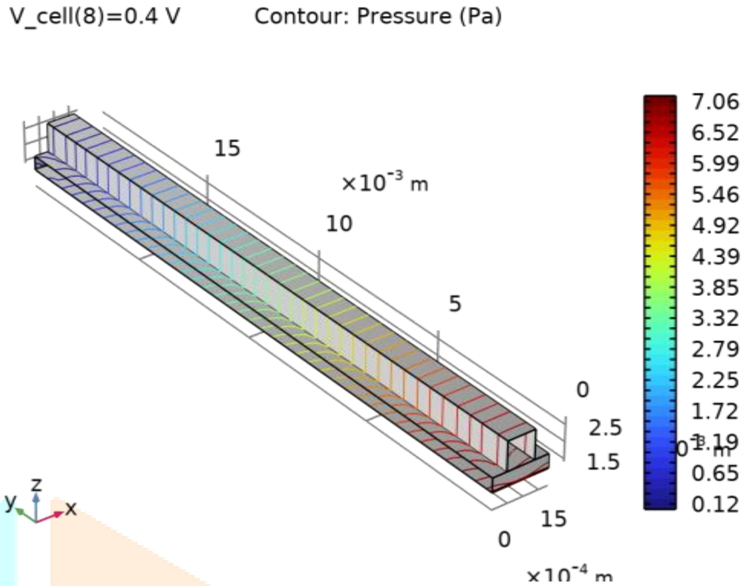


(c) H: W (5:4)

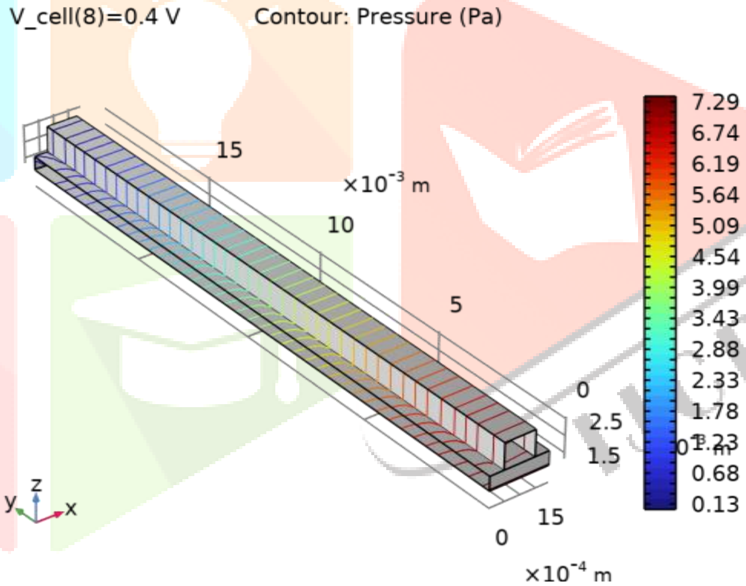
Fig. 6 - Shows the velocity magnitude at the cathode compartment under different designing conditions (a) Height and width are equal (1:1) (b) Height greater than the width (4:5) (c) Height less than the width (5:4).

F. PRESSURE PROFILE AT THE CATHODE

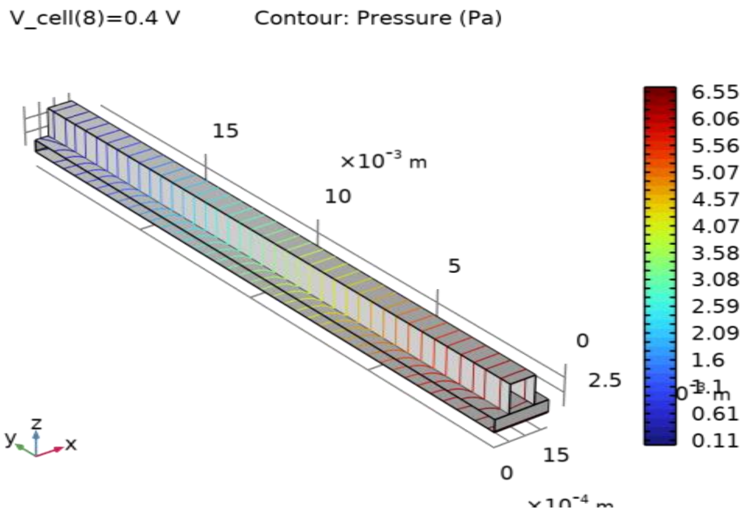
The pressure profile at the cathode compartment for the same voltage level. In some cases, channel height to width ratios is 4:5. Due to this case pressure profile at the cathode compartment is high at the same voltage level. Fig. 7 shows the pressure profile at the cathode compartment.



(a) H: W (1:1)



(b) H: W (4:5)



(c) H: W (5:4)

Fig. 7- Shows the pressure profile at the cathode compartment under different designing conditions (a) Height and width are equal (1:1) (b) Height greater than the width (5:4) (c) Height less than the width (4:5).

IV. CONCLISIONS

In this study, we have demonstrated three different ratios in the channel's height and width. These three ratios are 1:1, 4:5, and 5:4 and simulations have been found. In this study, we have drawn rectangular-shaped 3D channel geometries and these geometries have the same area of inlet and outlet of the channel due to which the inlet velocity of the channel will also be the same. In case width and height is equal (1:1) due to this condition the PEM fuel cell is generated a high current density (0.11056 mA/cm^2). Therefore, the structure and shape of the channel should be such that it is in square rectangular shape inlet area contact so that the fuel cell can generate more current. The following outcomes based on this research are:

1. The performance of the HT-PEMFC increases in case of height and width are equal (H: W) 1:1. Due to this case cell current density is high.
2. Comparison of findings from the 3-D fuel cell model with the experimental data.
3. The performance of ionic current density of the HT-PEMFC increases when the ratio of height and width is equal to 1:1. Due to this case cell membrane current density is high in the z compartment.
4. The velocity magnitude at the anode compartment is equal in all cases of the channel's height-width ratios at the same voltage level.
5. The case of the channel's height-width ratio is 4:5. In this case the pressure profile at the anode compartment is high at the same voltage level.
6. A case of channel height and width ratio is 4:5. In this condition the velocity magnitude at the cathode compartment is high, pressure profile at the cathode compartment is high at 0.4 V.

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