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PERFORMANCE IMPROVEMENT OF PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC) IN VEHICLE THROUGH GAS FLOW CHANNEL (GFC) USING CFD SIMULATION

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Abstract

This research presents the impacts of Gas flow channel designs on the performance of proton exchange membrane fuel cells were investigated using a three-dimensional computational fluid dynamics (CFD) model in ANSYS 2020 R1 FLUENT. The model was created with different gas flow channel arrangements of proton exchange membrane (PEM) fuel cells with straight, Serpentine, combined and with blockage flow channels. This study involves the CFD simulations of PEMFC under non-isothermal conditions; the simulation is run on 353 K and 3 atm to investigate the performance of fuel cells. The results show that gas flow channel design is affecting system performance in PEM fuel cells. At V=0.6V the current density value of full blockage of the flow channels with 2 and 3 blocks along the serpentine channels are 2.231 A/cm^2 and 2.311 A/cm^2. The experimental current density value at this voltage value is 1.391A/cm^2. The simulation results here give good agreement with experimental results data reported in the literature and the newly designed model. This gives high confidence for the results to determine the effectiveness of the flow field design in the Proton Exchange member fuel cell (PEMFC). At 0.6V the current density value increases from 2.338 A/cm^2 (serpentine) to 2.654 A/cm^2 (Biometric FC). The performance of PEMFCs with the Biometric flow channel is superior to that of other PEMFCs. This led us to a better design of the gas flow channel of PEMFC and improved hydrogen fuel cell vehicle performance.

Keywords: Computational fluid dynamics (CFD); Hydrogen fuel cell vehicle (HFCV); Gas flow channel (GFC); Proton Exchange Membrane fuel cell (PEMFC); Zero emission vehicle (ZEV)

1. Introduction

Global warming and air pollution in our world are a series of issues. As well known Human activities are the main cause of air pollution and global warming due to waste from industry, and transportation that uses a conventional engine that is gasoline and petrol engine. This increase in temperature together with a rise in the sea level will in the future make several places on the Earth uninhabitable [1].

The world's total energy consumption is highly dominated by the transport industry which accounts for nearly 55% of the world's energy consumption and 30.9% of carbon dioxide gas emissions according to recent research studies [3] [2]. According to recent research studies, nearly 55% of the world's energy consumption and 30.9% of carbon dioxide gas emissions are highly dominated by the transport sector [4][3]. Conventional vehicles are a major source of pollution emitting toxic gases like nitrogen oxides which contribute to the production of ground-level ozone (smog), acid rains, hydrocarbons, and other toxic air, Particulate matter (soot), etc. [5][4]. A zero-emission vehicle, or ZEV, emits no exhaust gas or other pollutants as a result of its onboard power source. In Tank-to-Wheel mode, a Zero Emission Vehicle (ZEV) is an electric vehicle that emits no CO^2.

Hydrogen Fuel cell vehicles as we see in the introduction part, the world continues to strive for clean and pure power sources to power various automobiles on the road, which are the primary contributors to hazardous pollutants released into the atmosphere from internal combustion engines. These toxic emissions contribute to climate change and air pollution and impact negatively people's health. To solve those problems automakers studied to develop zero-emission power train systems. Among those technologies fuel cell is one of the most popular types an alternative source of energy. It consumes hydrogen and oxygen as fuels and produces water vapor and heat as the only exhaust products. The fuel cell is an electromechanical device. Fuel cell vehicles are not only pollution-free, but they can also have higher efficiency making them an excellent choice for power generation. When comparing vehicles with hydrogen fuel cells with conventional engine vehicles it has better performance. On the other hand, conventional engines are limited to efficiencies of up to 40 % for diesel engines, and about 30 % for gasoline on the other side FC exhibits tank-to-wheel electric efficiencies of up to 60 % [7-9].

Internal combustion engine vehicles (ICEVs) are the primary source of urban pollution and greenhouse gas (GHG) emissions. The alarming levels of urban pollution are putting enormous pressure on the world automobile industry to switch from ICEVs to zero-emission vehicles such as electric vehicles (EVs) R. Kumar et al [13]. The transportation sector consumes 26% of total global energy and emits 13.1 percent of CO2 emissions [14].

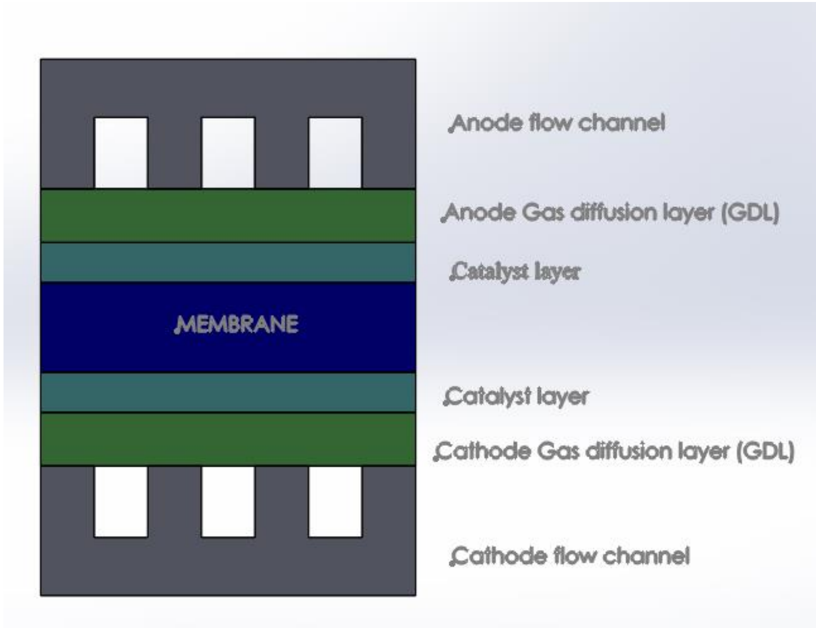


Figure 1. PEMFC components

Generally, in PEMFC the fuel cell stack consists of the following parts

- Gas flow channel (GFC)
- An electro-catalyst
- Proton Exchange membrane
- Gas diffusion layer (GDL)

PEM fuel can be made of the following components, namely an anode that accommodates the fuel, a cathode that supplies oxidant, and an electrolyte that separates the two electrodes known as the anode and the cathode and provides a passage for the transport of ions.

Both the electrodes those are the anode and the cathode have three distinct components: thus, are the gas diffusion layer (GDL), the gas flow channel, and the catalyst layers.

The fuel and the oxidant are distributed through the gas channel to the diffusion layer across the fuel cell. The gas diffusion layer and the catalyst layer are made of porous materials so that the fuel and the oxidant can be further transported from the diffusion layer to the catalyst layer where electro-chemical reactions take place to generate electricity.

Gas diffusion layer (GDL)

The gas diffusion layer (GDL) is the outer layer of the membrane electrode assembly (MEA) and it is placed between the gas flow channel and catalyst layer. It helps to uniformly distribute the reactants across the surfaces of the catalyst layers.

Catalyst

The purpose of the catalyst layer is to initiate hydrogen dissociation on the anode side and to speed up the oxygen reduction reaction on the cathode side. The protons pass through the membrane to the cathode side, where they react with oxygen and electrons from the external circuit to produce water and heat.

Membrane

The polymer electrolyte membrane is sandwiched between two electrodes which are known as an anode and a cathode. The proton exchange membrane conducts protons from the anode through the membrane that is used to complete the electrochemical reaction to the cathode. A polymer membrane is a slim plastic film that is permeable to protons, but it does not conduct electors.

Gas flow channel (GFC)

The gas flow channel (GFC) is a critical component that distributes fuel gases on the electrode surface while also removing water as a byproduct. Flow channels are physical flow paths manufactured on the BPs surfaces that serve as a guide for gas distribution throughout the BPs X. D. Wang et al. [14] [11]. The major role of flow fields in the membrane electrode assembly is to uniformly distribute the reactants to the following layers, known as the gas diffusion layer (GDL), and the reactants flow through the porous electrode to the active catalyst layer (MEA). Gas flow channels are curved into bipolar plates to provide pathways for reactant gases and, in practice, straight, serpentine, interdigitated, biometric flow fields are commonly used designs. Bipolar plates, also known as flow field plates, account for more than 60% of the weight and 30% of the overall cost of a hydrogen fuel cell vehicle's fuel cell stack Palencia et al. [20] [14] . It is one of the most essential components for cost reduction and performance improvement in a PEMFC stack is the design of an adequate flow field channels layout. Improvements of up to 50% of the original output power density are possible.

Generally, Flow fields' primary function is to evenly distribute reactants to the gas diffusion layer (GDL) and then to the next layer, the active catalyst layer in the membrane assembly (MEA), via the porous electrode J. Shen et al. [28] [16]. A well-designed bipolar plate flow field is the major player in these processes. Homogeneous current and temperature distribution, as well as effective water removal, are key functions in a PEMFC that need careful flow field design. BPPs are used to electronically connect one cell to the next in an electrochemical cell stack by supplying reactant gases to the electrodes through flow channels. These plates also provide structural support for the MEAs, which are thin and mechanically weak, as well as a way to control water within the cell. The BPPs also help with heat management in the absence of specific cooling plates Li & Sabir [34] [18].

A better flow field design should also remove water efficiently, prevent water condensation, and provide sufficiently high moisture content in the membrane [35] [19] . The gas diffusion layer comprises > 60% of the weight and 30% of the total cost of the FC stack. A good design of the FFP can thus improve the overall PEMFC stack performance in terms of costs by as much as 50%.

The flow channels in the PEMFC are essentially used to distribute the fuel gases on the electrode surface and remove the by-product water. Therefore, the types and dimensions of flow channels play an essential role in the performance of PEMFC.

Different flow field geometric configurations can be recently found in many pieces of works of literature. Each of those geometrics configurations shows its advantages and disadvantages depending on the PEMFC operating conditions for which they were designed. Well, the design of the flow channel in bipolar plates is one of the important factors for the cell performance of a PEM fuel cell system. Some of the flow channel designs.

- Straight parallel flow filed
- Serpentine flow field
- Pin flow field
- Leaf-shaped flow fields
- Interdigitated flow field
- Cascade flow field
- Bio-metric flow

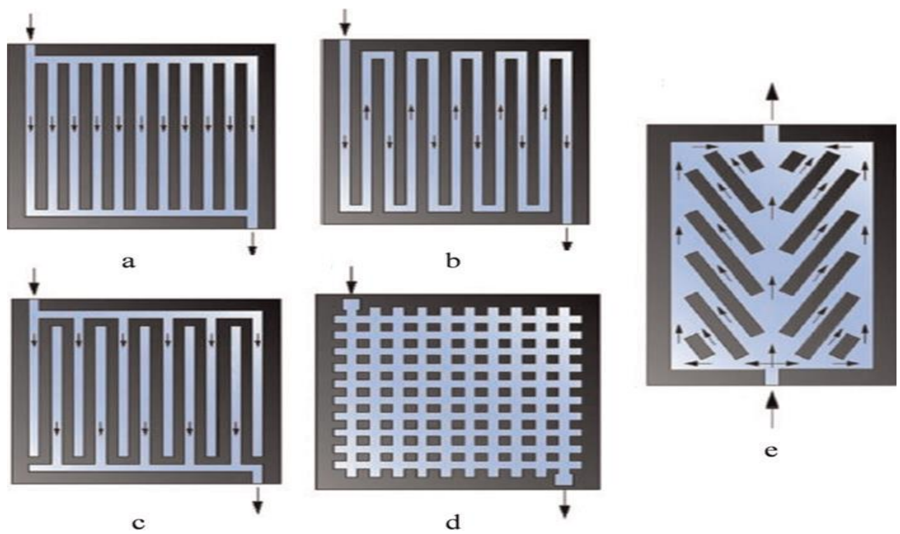


Figure 2. Various flow fields used in PEMFC (a) Straight flow field channel, (b) Serpentine flow field channel, (c) Interdigitated flow field channel, (d) Pin-type flow field channel, (e) Bio-inspired flow channel [20].

Effect Gas Flow Channels (GFC) in PEMFC Performance

Weng et al. [31] investigated the fuel cell model by the distributions of oxygen concentration on the parallel, serpentine, and interdigitated flow field. The results indicate that the parallel flow field fuel cell has the worst cell performance due to non-uniform flow distribution.

A paper that was published by Ghasabehi et al. [43] [23] presented a numerical model of mass transport in a PEM fuel cell with partial blocks introduced in the gas channel.

The flow channel was then finished with narrowed ribs opposing the protuberances, which improved PEM cell performance by about 8% among all flow field designs. However, the pumping power to pressurize the gas is a significant trade-off. Dawes et al. [12] [18] in this work, a three-dimensional PEMFC model has been developed and is used to investigate the effects of water flooding on cell performance parameters. This paper presents the results from a three-dimensional, single-phase, fuel cell model, coupled with an effective diffusivity algorithm.

Effect of shape of the flow channel

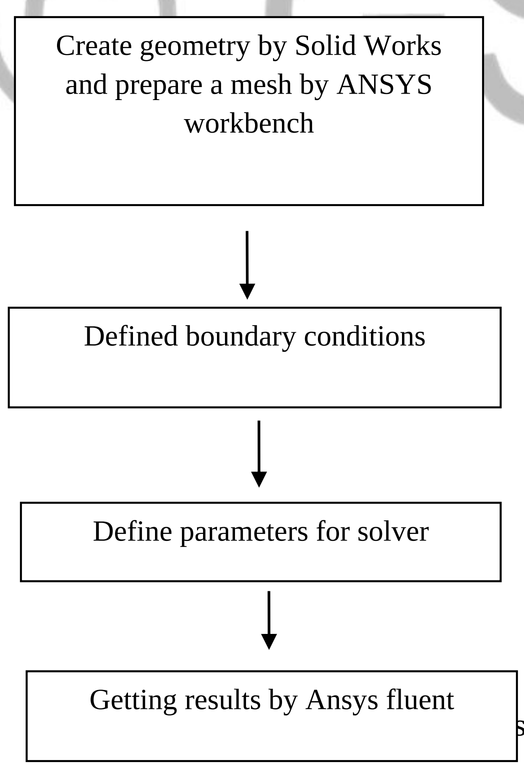
Ming & Su [37] [21] in this article, the PEMFC performance will be improved by using a parallel flow channel with a step-wise depth design, as both experiments and predictions show. However, the performance of the PEMFC in the serpentine flow channel is unaffected by the depth of the flow channel.

Effect of straight and serpentine flow channel

Hashemi et al. [18] [12] The researchers concluded that serpentine design produces better results, but it does so at the expense of a bigger pressure drop along with the cell.

MATERIAL AND METHODOLOGY

A three-dimensional fuel cell model was created, and simulations were run using the computational fluid dynamics (CFD) software ANSYS FLUENT. Each bipolar plate material's effect on cell performance. Significant parameter distributions such as temperature, pressure, hydrogen mass freaction, oxygen, and current density are presented alongside cell performance.



Choosing the right modeling parameters is important in establishing the base case validation for the model against experimental results. Very limited experimental results are available in the literature with detailed specifications of the cell geometry and experimental conditions. However, courtesy of Fatemeh Hashemi et. al, in [12]simulation results used to verify her 3-D model were made.

Table 1. PEMFC Dimensions [15]

Cell dimensions	symbols	Values (mm)
Channel length	L	10
Channel height	H	5.1295
Height of gas channel	H	1
Width of the gas channel	w	1
Width of the cell	w_{cell}	2
Thickness of catalyst layers	t_{cl}	0.014
Thickness of gas diffusion layers	t_{dl}	0.0254
Thickness of membrane	t_{mem}	0.051
Thickness of current collectors	$_{cc}$	2.5
Serpentine channel length	l	5
serpentine-channel width	w	4

The operational parameters are based on the experimental operating conditions used by Wang et al. [22].

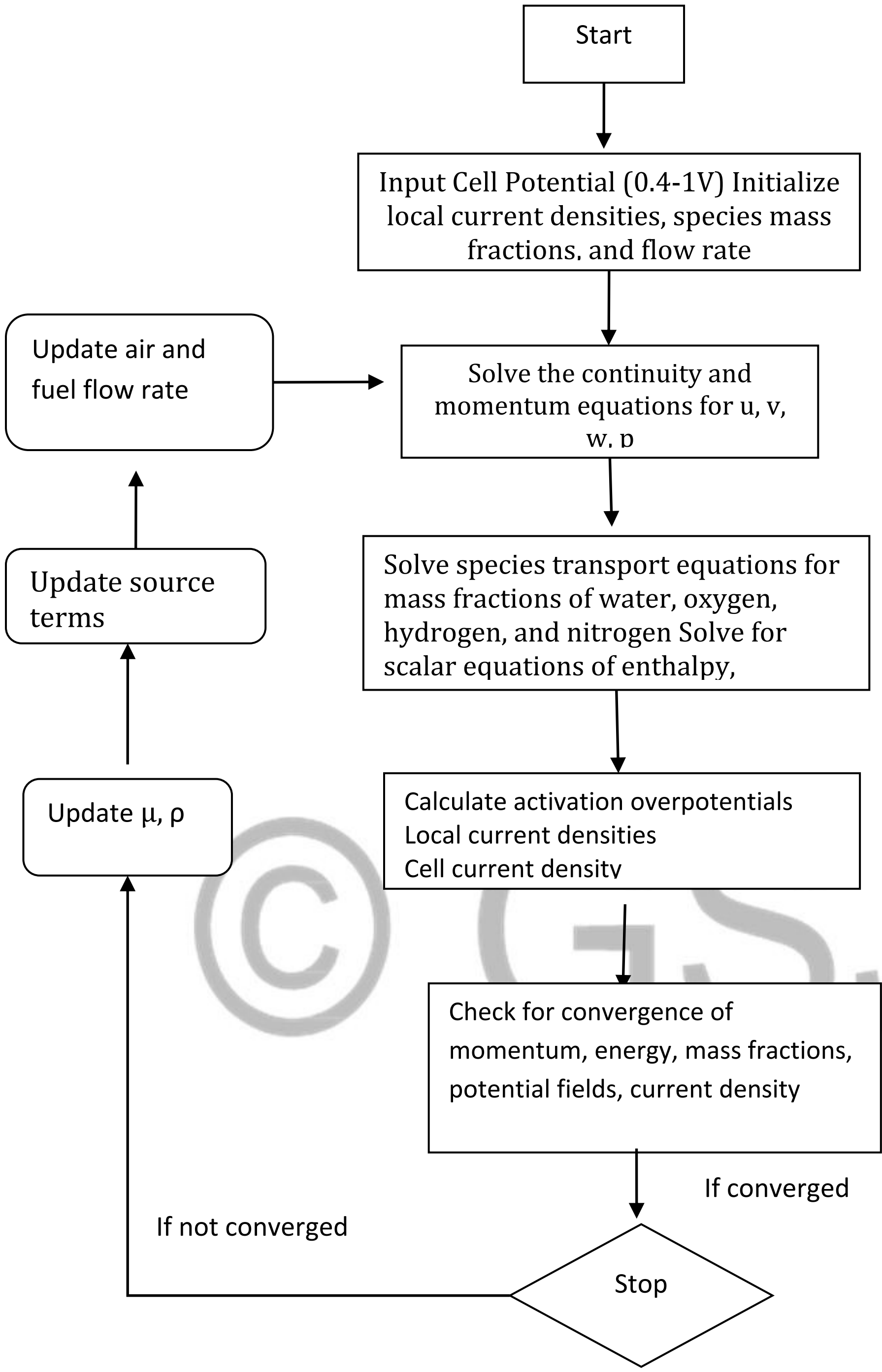


Figure 4. A solution algorithm for solving governing equations in proton exchange membrane fuel cell (PEMFC).

3.1.Numerical modeling

3.1.1. Geometry of PEMFC

The simulated fuel cell geometry model of PEM fuel cells consists of flow channels of anode and cathode, gas diffusion layers, catalyst layers, and proton exchange membrane as main components.

Table 1 Boundary conditions of the model

Boundary condition	Location		values	units
Velocity inlet	Inlet Anode	Inlet gas velocity	2	m/s
		Inlet Hydrogen mass fraction	0.3	-
		Inlet water mass fraction	0.7	-
	Inlet Cathode	Inlet gas velocity	2	m/s
		Inlet Oxygen mass fraction	0.14	-
		Inlet water mass fraction	0.2	-
Pressure outlet	Outlet Anode	Outlet gas pressure	0	pa
	Outlet Cathode	Outlet gas pressure	0	pa
Wall	Terminal Anode	Specific electric potential	0	V
	Terminal Cathode	Specific electric potential	0.6-0.9	V

Table 3. Parameter values

Description	value	Units
Cell operating temperature	353	k
Cell operating pressure	3	Atm
CL Porosity	0.6	-
GDL Porosity	0.6	-

Original PEMFC flow channel Model

a) b)

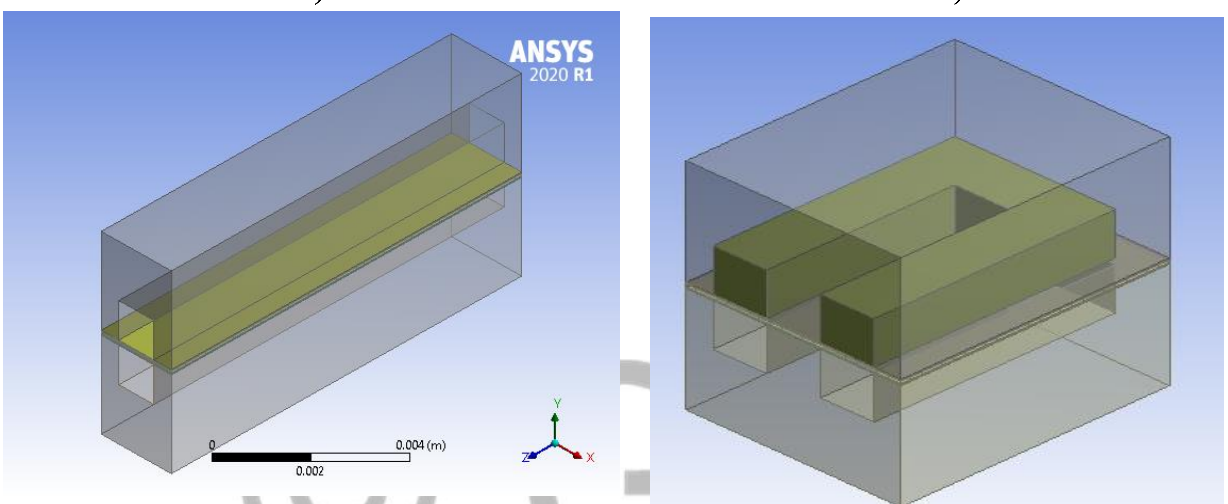


Figure 5. An original 3-D view of the straight channel and serpentine flow channel PEMFCa) Straight FC b) Serpentine FC

Before going to the modified finite element analysis, the model of the PEMFC in solid work is made. The model of the PEMFC shows-below made in solid work 2016. The parts parameter and dimension are used from references [12]and [13]. 3D PEMFC models were created by the following dimensions for straight type one the length is 10mm, the width is 2mm, and the height is 5.1298mm for the serpentine type of the flow channel the length is 5mm, the width is 4mm, and height 5.1298mm. The dimension of flow channels is 1x1x10mm and 1x1x4.5mm for straight and serpentine respectively.

3.1.1.1.A modified model of PEMFC flow channels

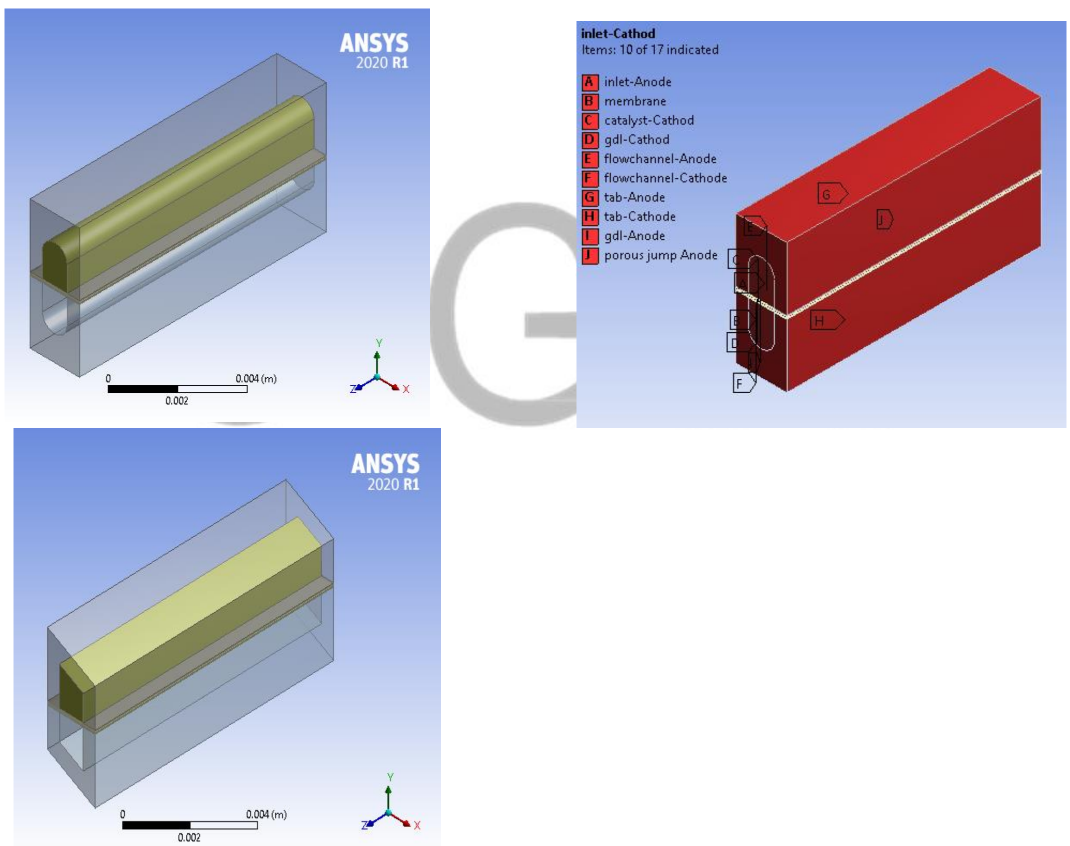
The main purpose of those models is to improve the performance of PEMFC vehicles by considering the design of gas flow channels. Depending on different models of flow channels it is possible to get a better mass fraction of Hydrogen and Oxygen, temperature, pressure, and velocity distribution.

Straight-type flow channel

The original paper flow channel shape was rectangular modifying the shape can get different results that approximate the existing results.

Flow channel size of 1x1x10mm replaced by 1x1x10mm with radius 1mm, 1x1x10mm with inclined angle 1.5mm.

a)



b)

c) d)

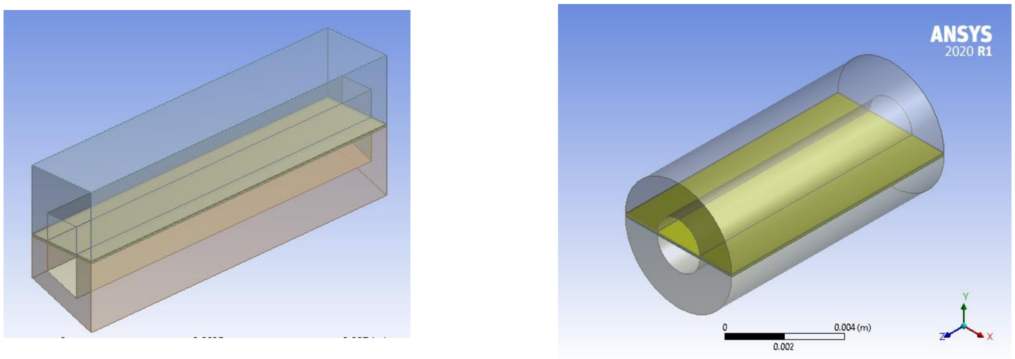
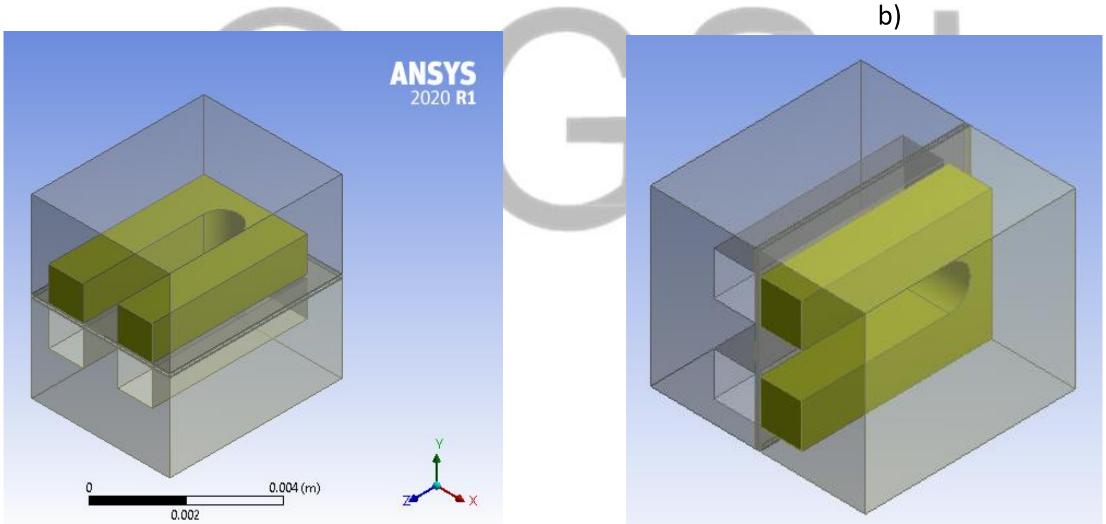


Figure 6. Straight flow channel a) Curvy radius b) both inclined electrodes c) Cathode inclined d) circulated flow channel Serpentine-type PEMFC flow channel

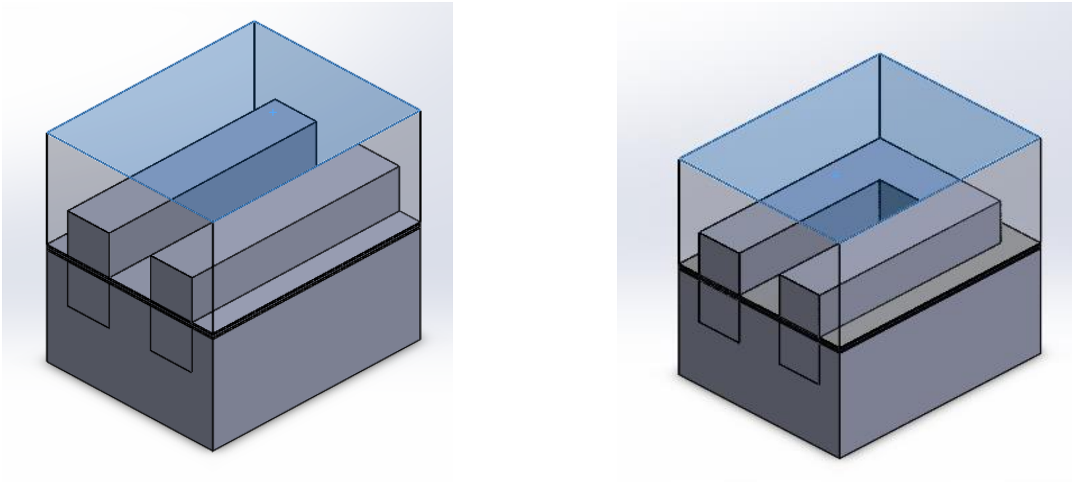
In this type of model, there are a variety of designs with internal curvy radius, vertically assembles MEA, combined FC (Combination of the straight and serpentine fuel cell) Combined straight and serpentine flow channels.

b)



a)

Figure 7. Serpentine flow channel a) curvy flow channels b) curvy with vertically assembled



a) b)

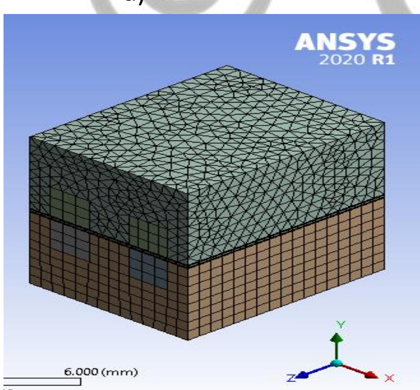
Figure 8. Combined a) combined with Anode straight and cathode serpentine b) combined with Cathode straight and Anode serpentine

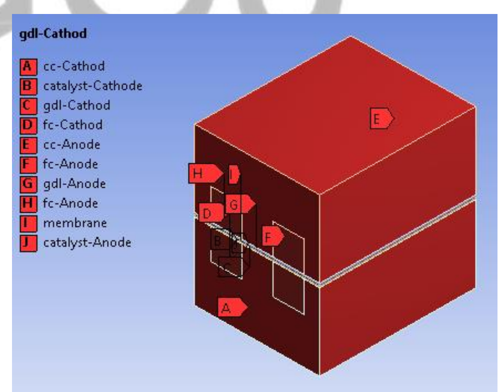
Anode with straight flow channel and Cathode flow channel

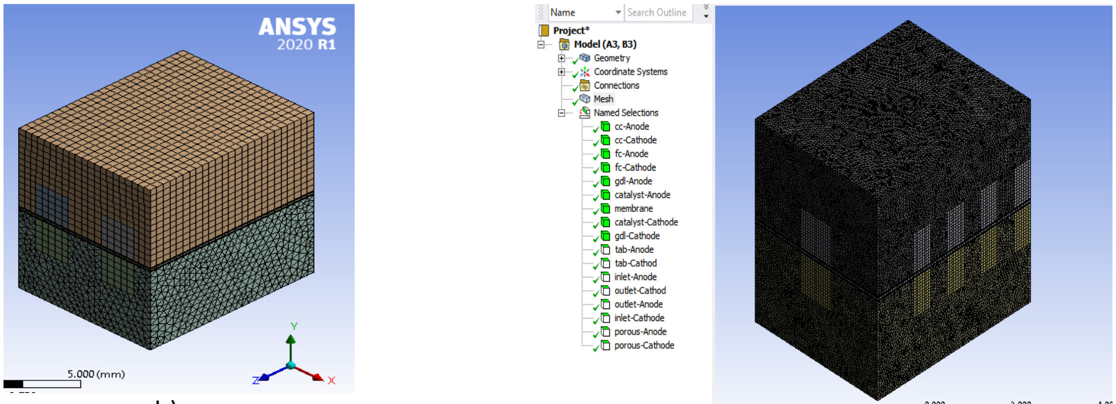
Finite element meshing of the PEMFC parts

Finite element modeling made with ANSYS 2020R1 Workbench. The model components are drawn by SOLIDWORKS software and then imported to the ANSYS FLUENT Workbench.

a)







b) c)

Figure 9. The meshing of the PEMFC parts a) Anode serpentine b) cathode serpentine c) biometric

Model validation

To validate the model established in this study, comparisons have to be made between the simulation results corresponding to the base case conditions and the experimental results reported by [22]and article[12]. A polarization curve (cell voltage v_s. current density curves) is a graph that shows how well a fuel cell performs.

In the present computation (CFD) with the experimental data, a good agreement is seen between the sets of results through the current density ranges observed as shown below in Figures.

Validations: comparison between experimental data and polarization curve for the present computation (CFD).

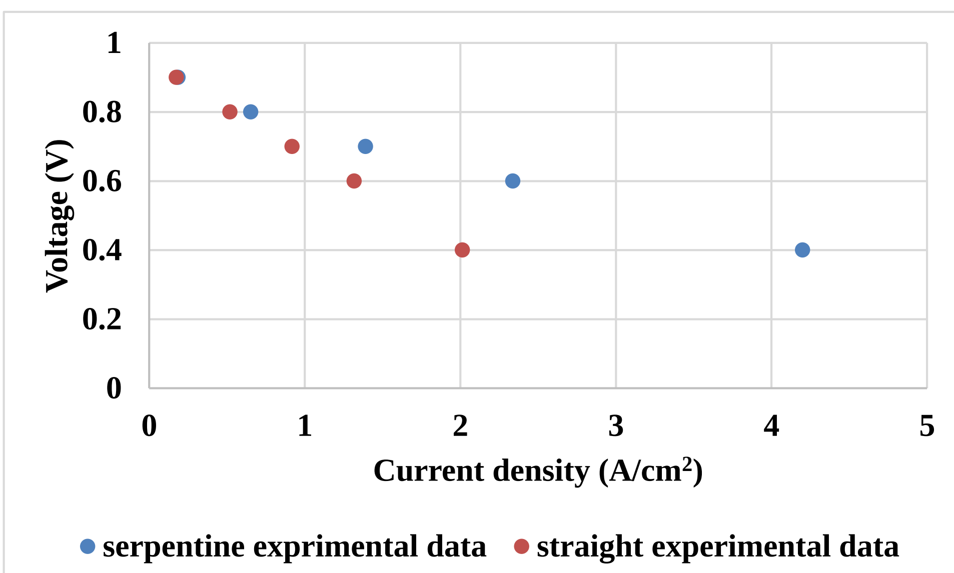
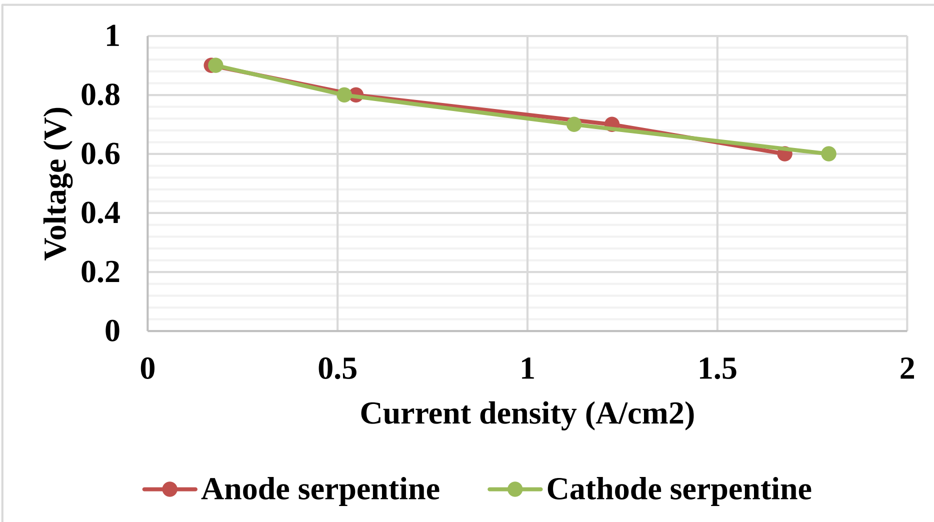


Figure 10. Comparison of simulation results between straight-type and serpentine-type flow channel

To compare the performance of PEM fuel cells with serpentine and straight flow fields the simulations were conducted. The model findings revealed that the serpentine flow field shows a better distribution of current density. Simulation results were compared with the experimental data reported in the literature and universal comparisons showed good agreement between our



model and experimental results.

Figure 11. Comparison of simulation results between combination types With only Anode and only cathode serpentine

One of the objectives of this paperwork is the Comparison of a new model of PEMFC with the existing experimental data as we saw on the above graph when the voltage value decreases there is a big difference with the existing experimental data. Generally, in combined type serpentine flow has a similar polarization curve but still needs modification for enhancing the performance.

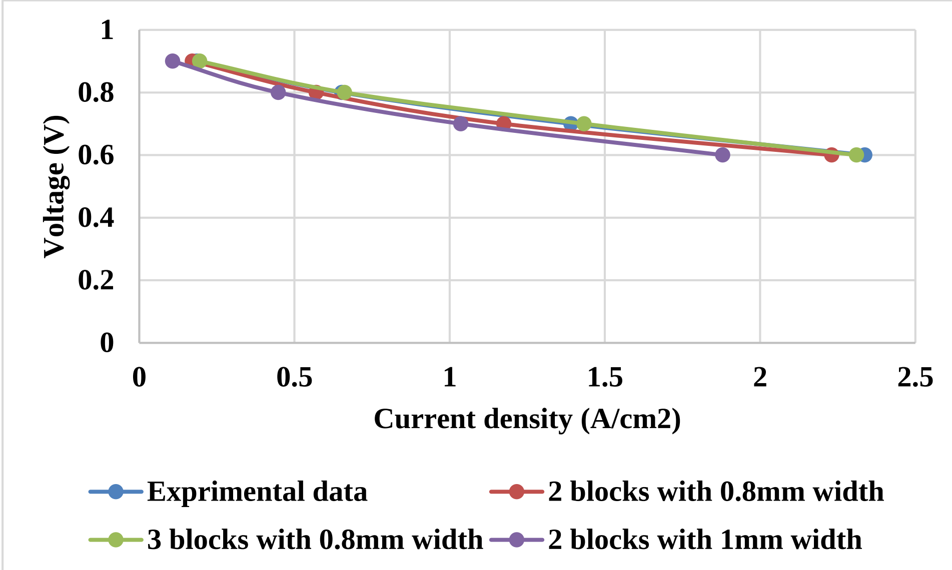


Figure 12. Comparison of simulation with different blockage numbers and sizes and experimental results

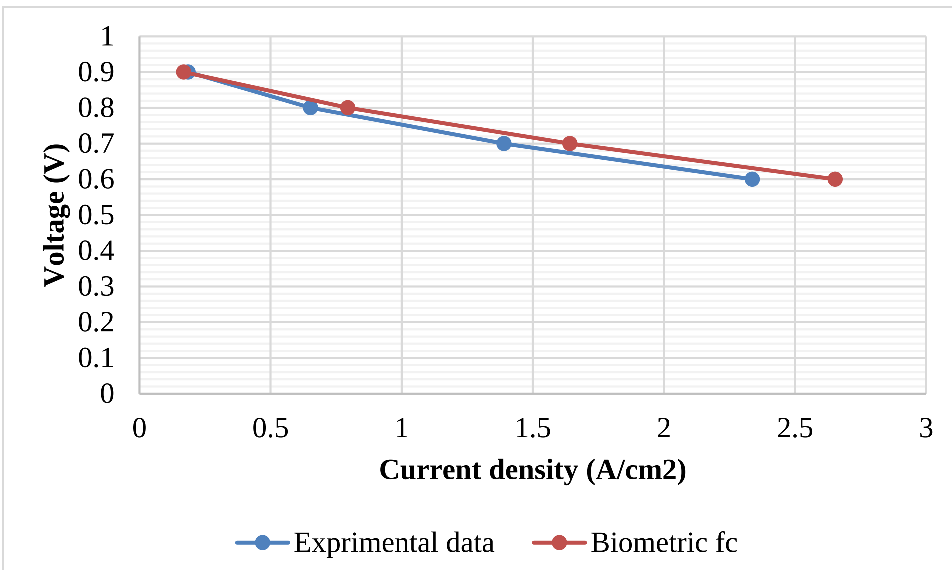


Figure 13. Comparison of simulation biometric flow channel and experimental results

Straight gas flow channel

Concentration distribution of reactants

Distribution of mass fraction of hydrogen (anode) and oxygen (cathode) in the PEM fuel cell with a straight channel for different shapes of gas flow channel. The mass fraction distribution of hydrogen and oxygen in the PEM fuel cell with the serpentine channel is also indicated in the below figures.

Distribution of mass fraction of Oxygen

At 0.6 V and 353.15 K

With inclined type flow channel

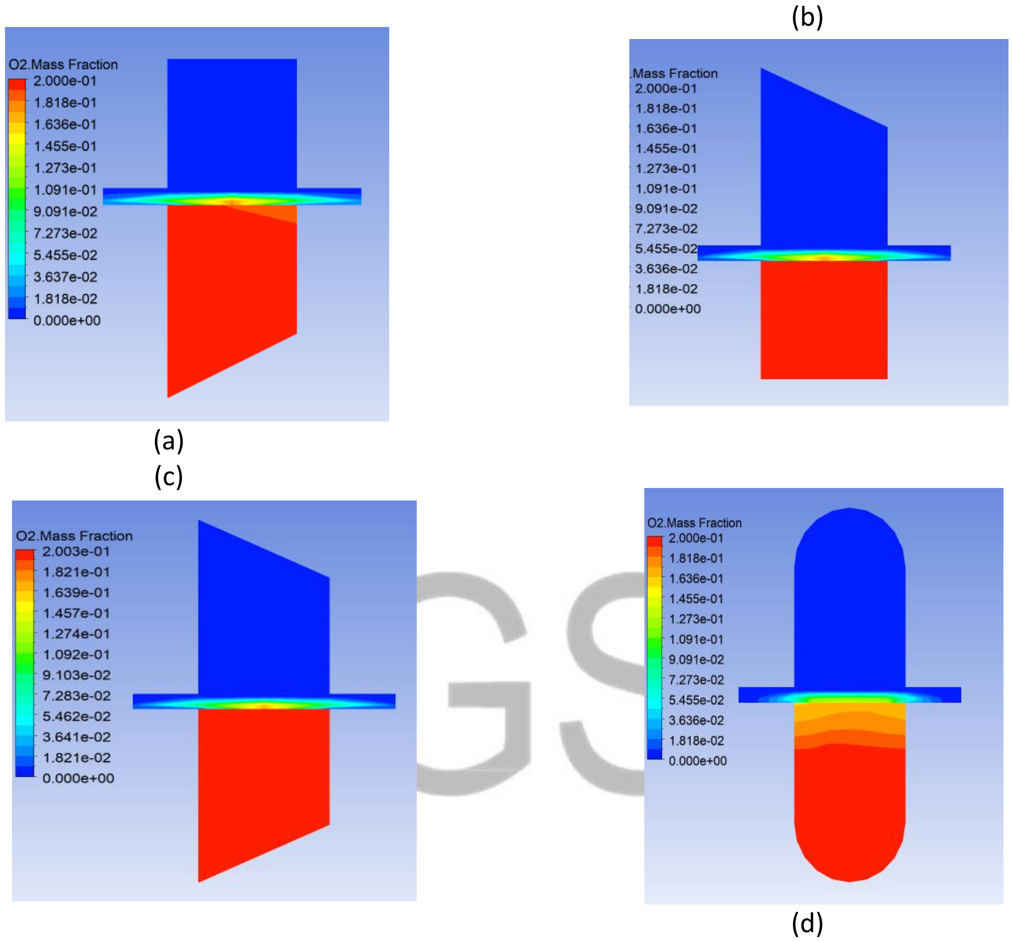


Figure 14. Distribution of mass fraction of Oxygen a) Cathode inclined b) Anode inclined c) both inclined d) curvy flow channel

The distribution of the mass fraction of Oxygen from the above figure has identical distribution for inclined type and curvy type flow channels. Under the current collector, oxygen is more depleted in the MEA region.

Distribution of mass fraction of Oxygen

At 0.6 V and 353.15 K

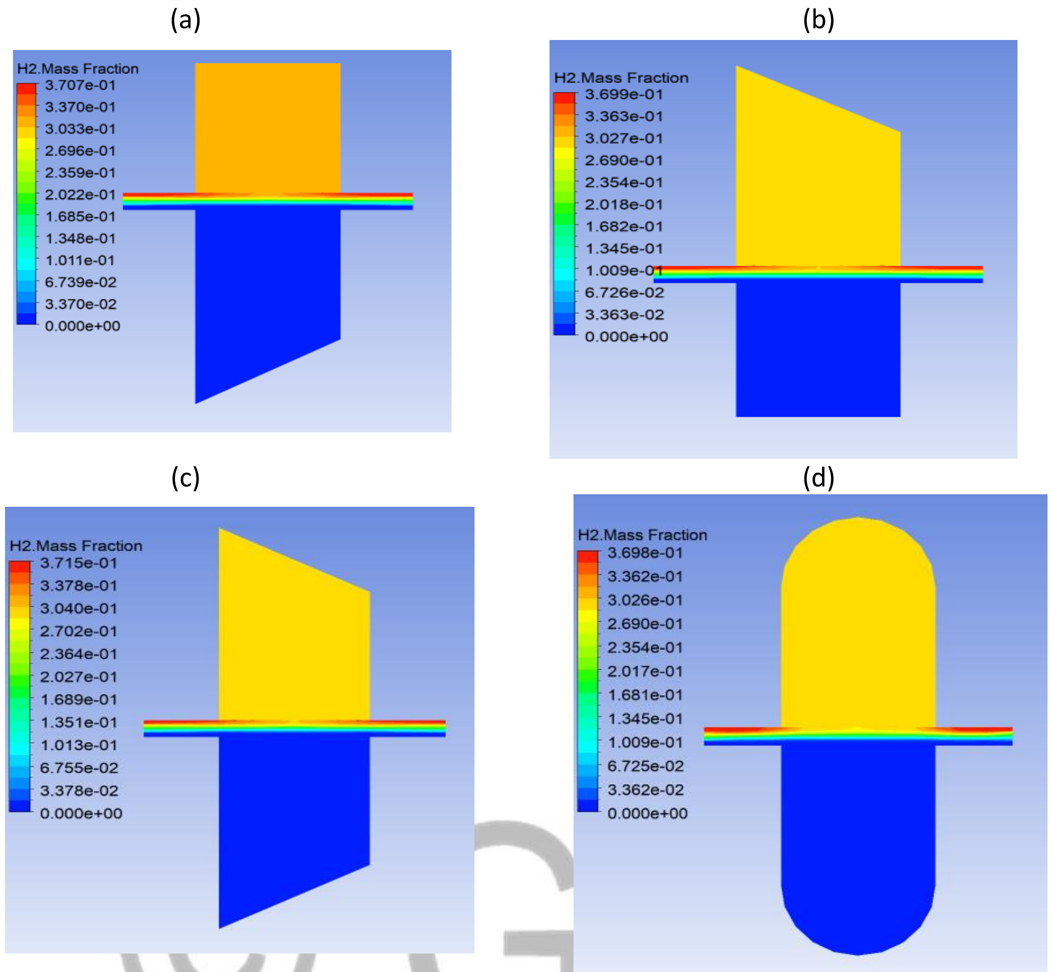


Figure 15. Distribution of mass fraction of Hydrogen a) Cathode inclined b) Anode inclined c) both inclined d) curvy flow channel

To improve the performance of (the PEM) fuel cell, it is very important to know the hydrogen transport along the anode side. There is higher hydrogen mass fraction distribution through the membrane, anodes' catalyst, and gas diffusion layers. From the above figure a and c have approximated hydrogen mass fraction.

From above Figure 4.6 distribution of the mass fraction of Hydrogen (c) and (d) is 0.3715 and 0.3698 respectively which means there is high hydrogen distribution on the inclined type flow channel.

Temperature distribution in the fuel cell

As shown in the simulation results below for the straight inclined type there is a high concentration temperature at the interface between catalyst layers and membrane.

The maximum temperature values are almost similar for all types of inclined flow channels. There higher temperature concentration at the inlet than the outlet for both anode and cathode.

At 0.6 V and 353.15 K

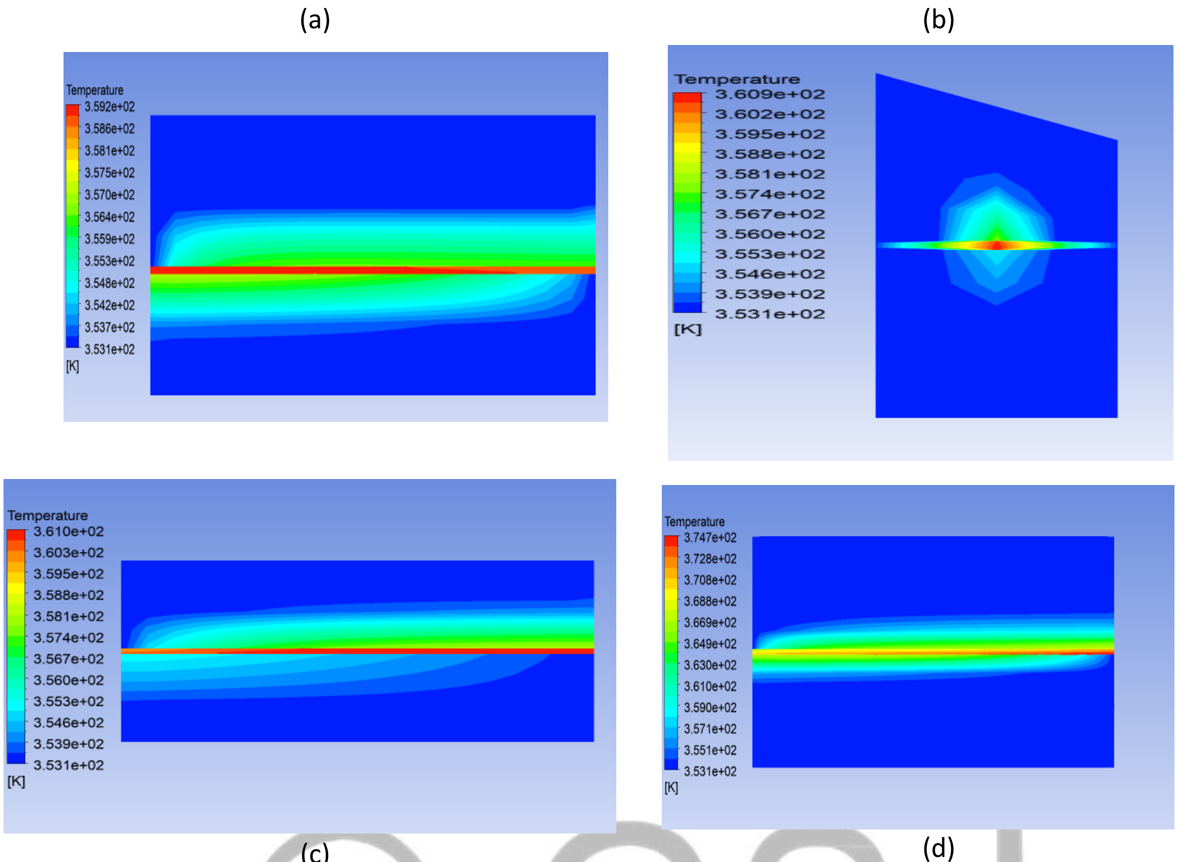
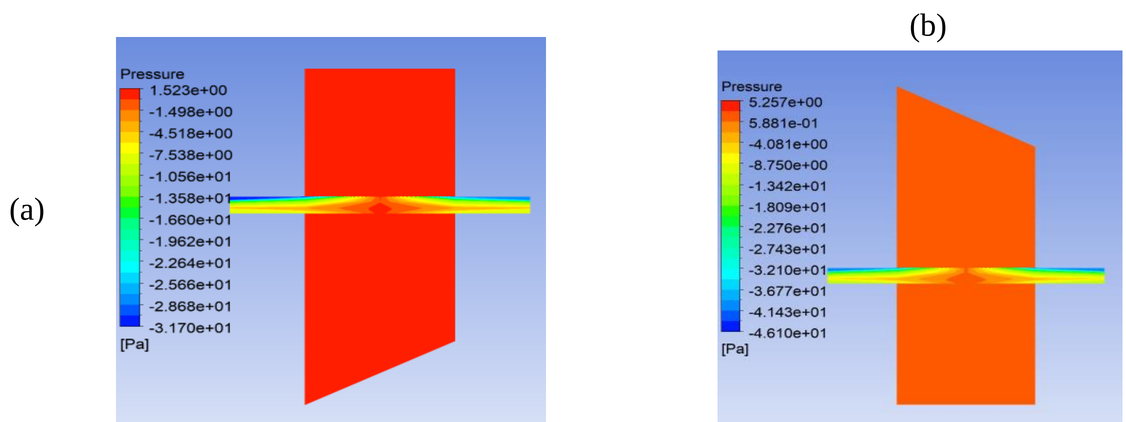


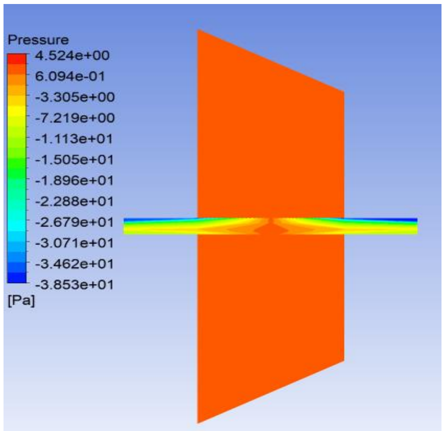
Figure 16. Temperature distribution in the PEMFC a) Cathode inclined b) Anode inclined c) both inclined d) curvy flow channel

The temperature distribution of the curvy type flow channel is higher than the inclined one. For a curvy type flow channel, there is a higher concentration temperature between an outlet of an anode and an inlet of the cathode at the interface between catalyst layers and membrane.

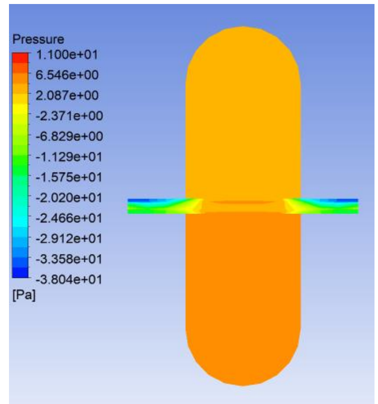
Pressure distribution in the PEMFC

At 0.6 V and 353.15 K





(c)

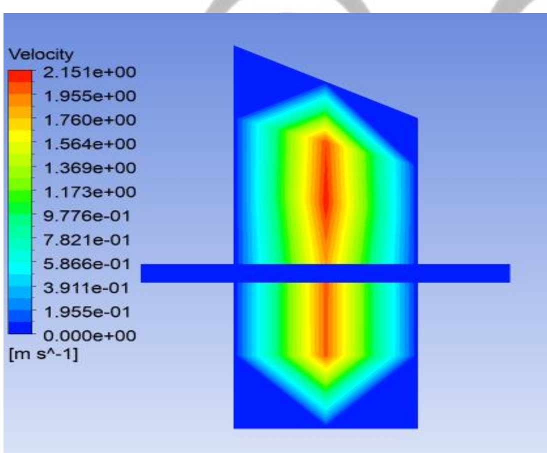


(d)

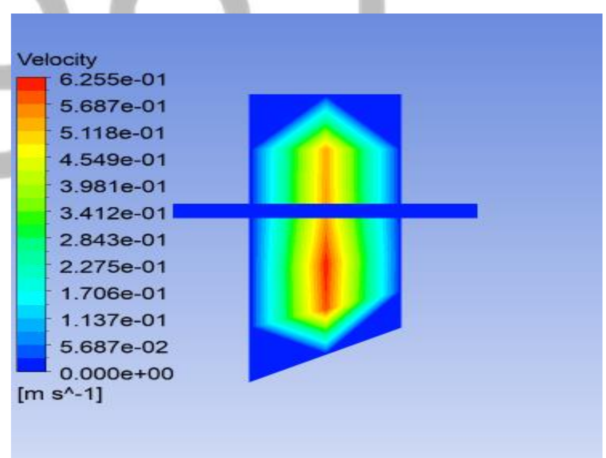
Figure 17. Pressure distribution in the PEMFC a) Cathode inclined b) Anode inclined c) both inclined d) curvy flow channel

Flow velocity

The flow velocity of PEMFC is influenced by different flow-field designs.



(a)



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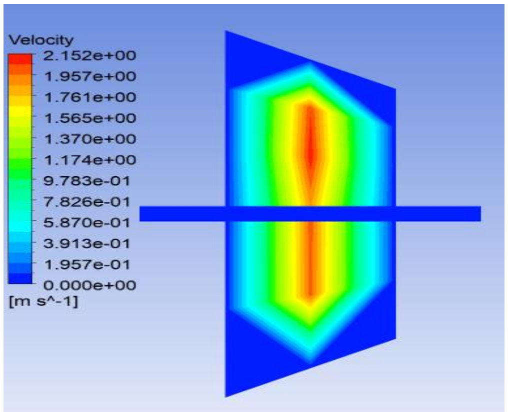
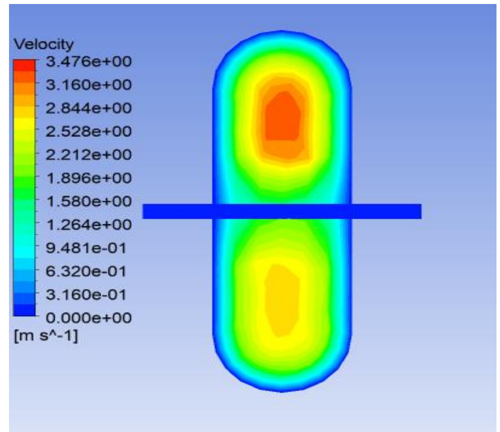


(c)



(d)

Figure 18. Flow velocity a) Cathode inclined b) Anode inclined c) both inclined d) curvy flow channel

For the straight with inclined flow field, the maximum local velocity is 6.255m/s, 2.151m/s, and 2.152m/s for cathode inclined, Anode inclined and both inclined respectively. The flow velocities for the above Figures A and b above are almost identical but there is a big difference with cathode cathode-inclined type. Therefore, to get a higher flow velocity of PEMFC only by focusing on the Cathode flow channel. From above Figure a has the highest flow velocity. There is no flow velocity between the Gas diffusion layers (GDL) of both electrodes.

There is high flow velocity at the outlet of the Anode and cathode even though the maximum flow velocity exists at the Anode outlet.

Generally, from straight-type flow channels with different types of flow channel designs the distribution of the mass fraction of Oxygen is almost similar there is no big difference. Therefore, the flow channel design on the Anode part does not have that much effect on activity. The distribution of the mass fraction of Hydrogen, temperature distribution, pressure distribution, and flow velocity show different values which mean those parameters are affected by the flow channel design. Temperature distribution for all inclined types of flow channels is uniform (360 K), but at curvy type, there is a higher temperature distribution (375 K). Pressure distribution is highly sensitive to the variety of design of flow channels.

Serpentine flow channel

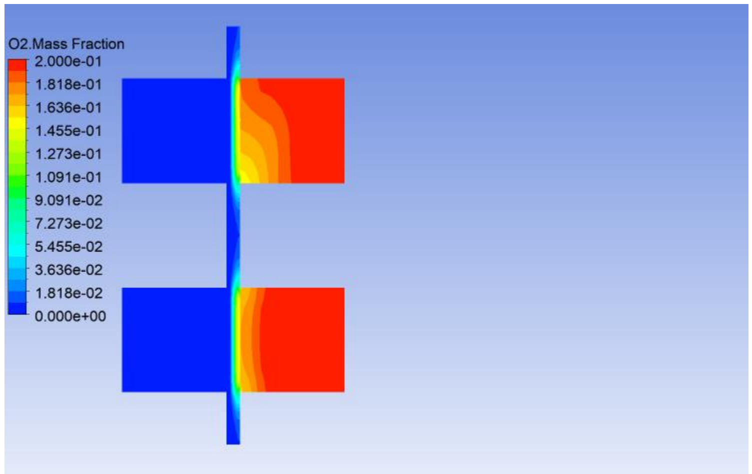
It is commonly referred to as an industrial standard because it is one of the most prevalent and practicable channel configurations for existing PEM fuel cells.

There is a different design of serpentine flow channel with curvy radius, vertically MEA gas flow channel, combined type (anode serpentine and cathode straight type and the reverse) and biometric flow channel. Consider

Mass fraction distribution under 3 atm 353.15k and the conditions at 0.6 volts

At 0.6 V and 353.15 K

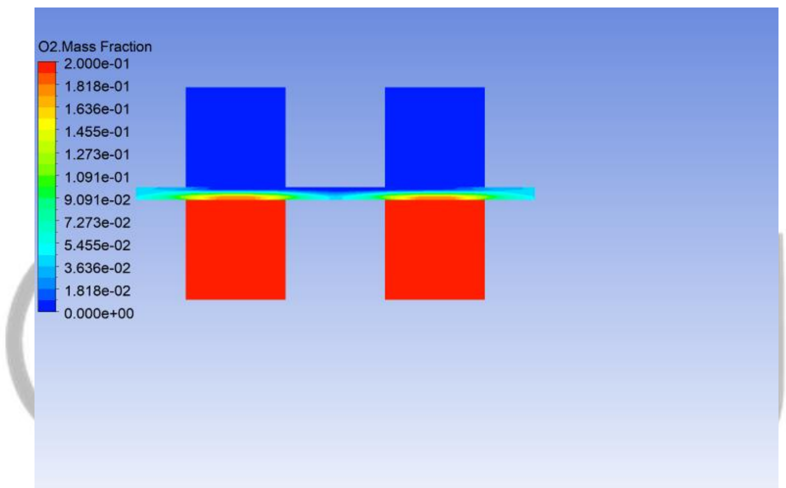
Vertically assembled membrane



(a)

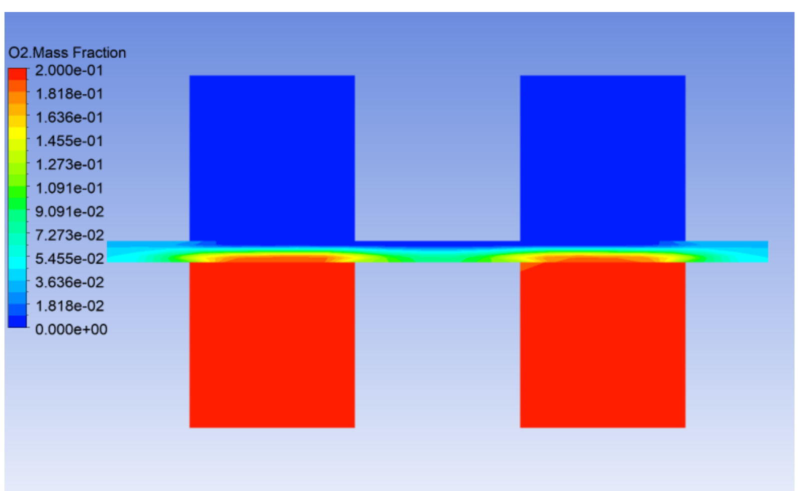
Combined anode serpentine

Anode serpentine



(b)

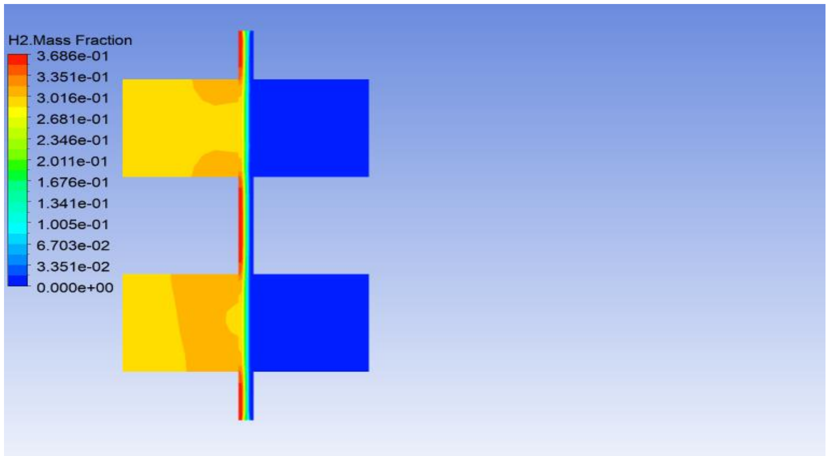
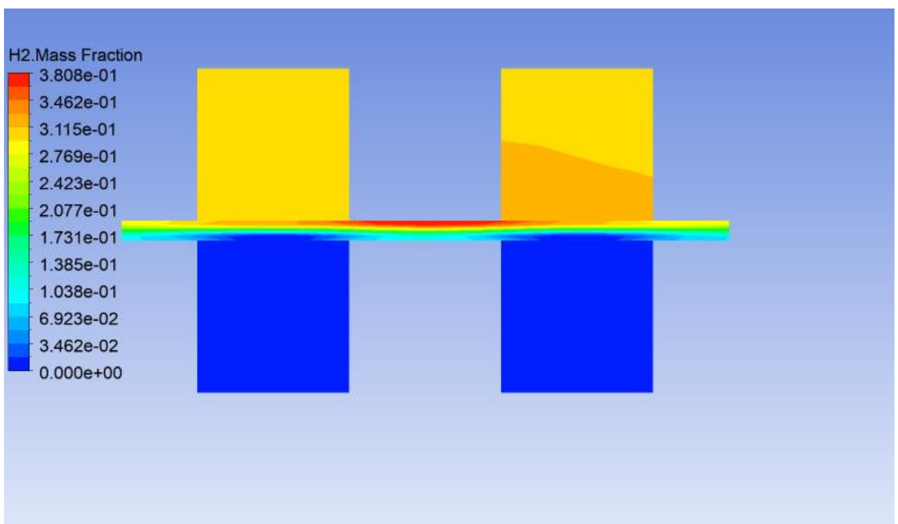
Cathode serpentine



(c)

Figure 19. Distribution of mass fraction of oxygen

Distribution of mass fraction of Hydrogen

	At 0.6 V, 3 atm, and 353.15 K
Vertically assembled membrane	 (a)
Anode serpentine	 (b)

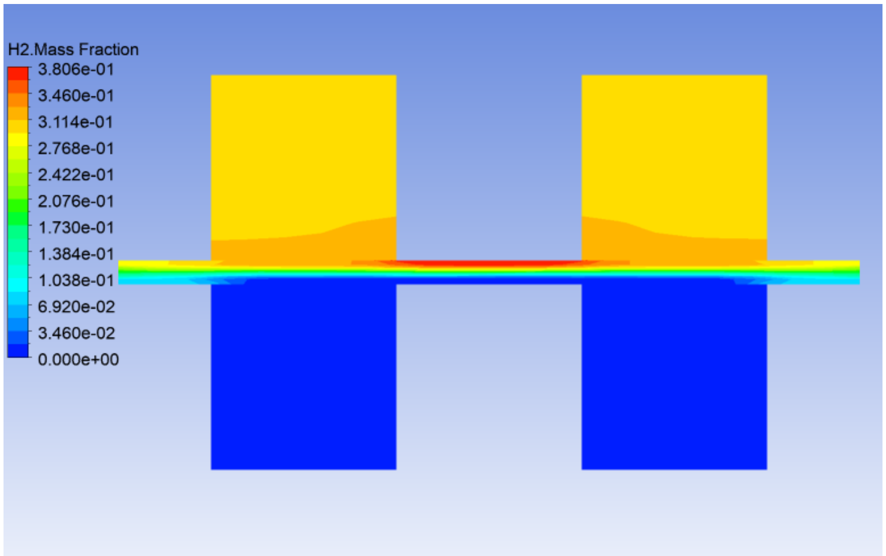
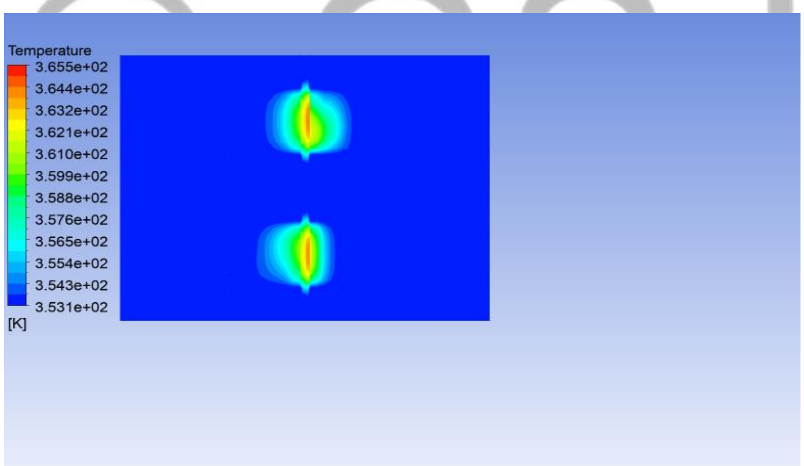
Cathode serpentine	 (c)

Figure 20. Distribution of mass fraction of Hydrogen

Temperature distribution

Vertically assembled membrane	 (a)

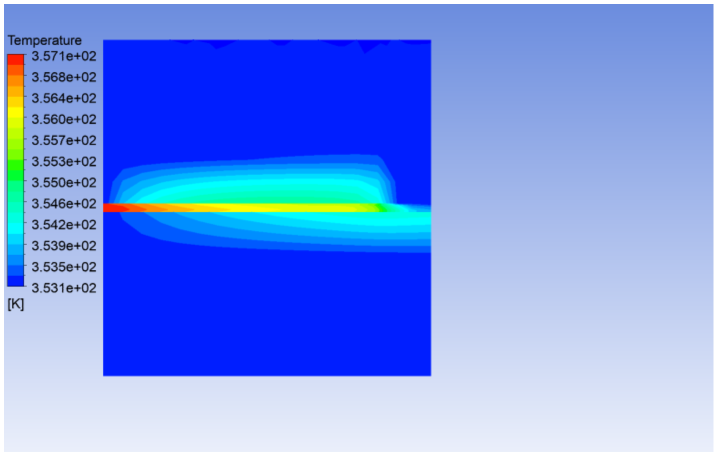
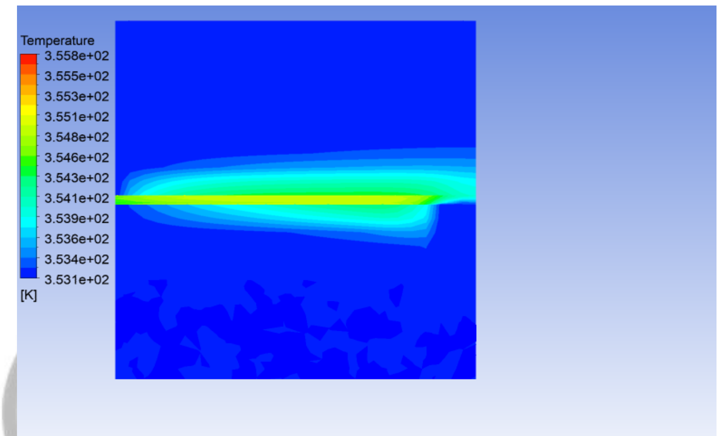
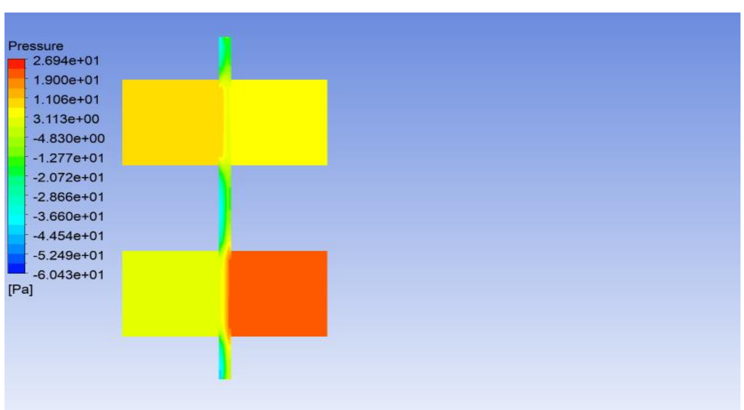
Anode serpentine	 (b)
Cathode serpentine	 (c)

Figure 21. Temperature distribution in the PEMFC

Pressure distribution in the PEMFC

Vertically assembled membrane	

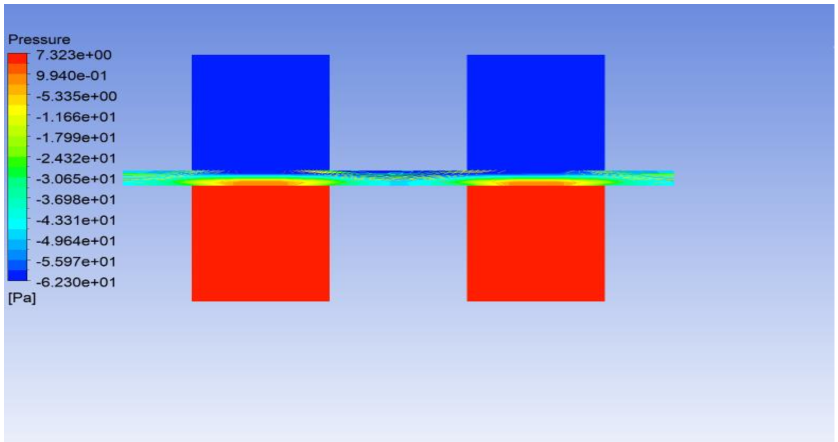
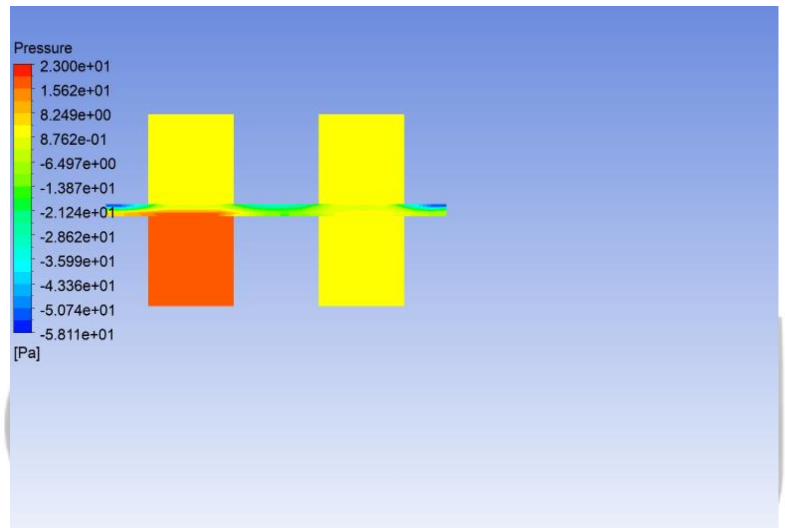
Anode serpentine	
Cathode serpentine	

Figure 22. Pressure distribution in the PEMFC

Velocity distribution

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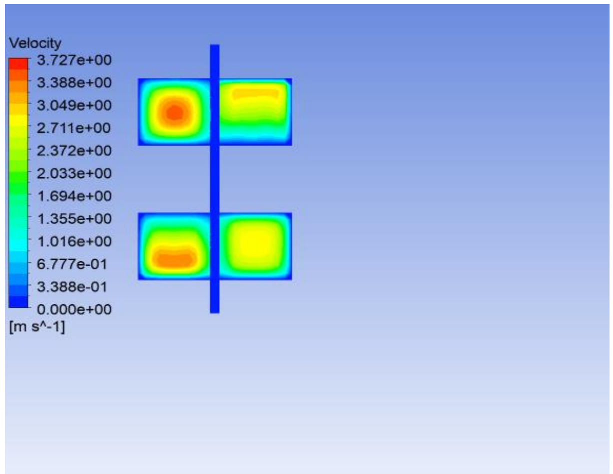
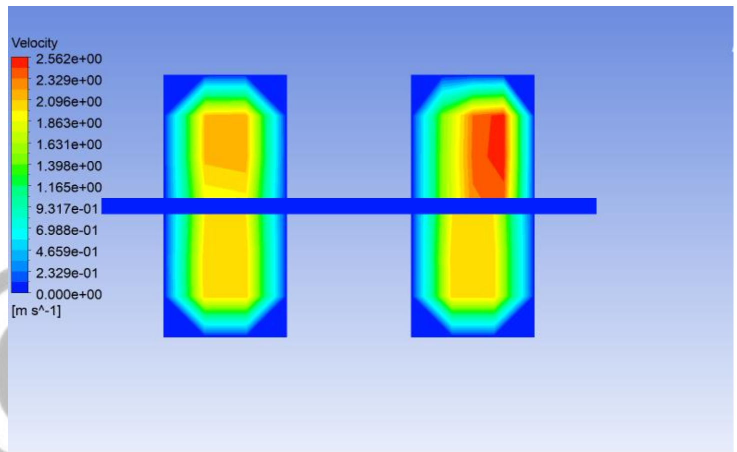
Vertically assembled membrane



Anode serpentine



Cathode serpentine

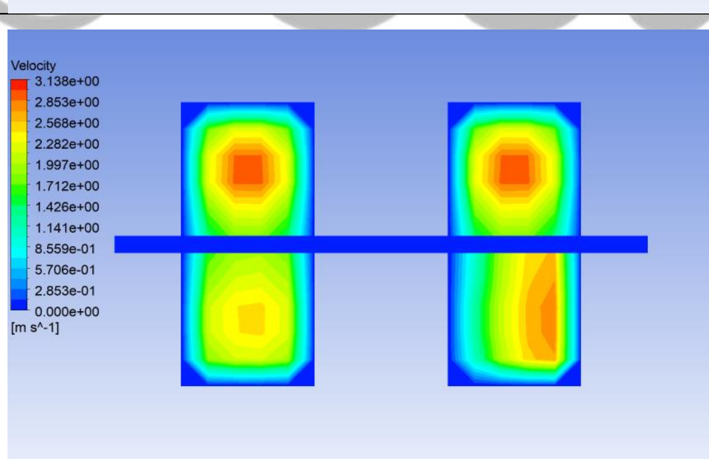


Figure 23. Velocity distribution in the PEMFC

There is a higher maximum value of velocity and pressure in anode straight and cathode serpentine combined type of flow channel. In the other type combined flow channel cathode straight and anode serpentine higher temperature maximum value by 1.74k.

Biometric

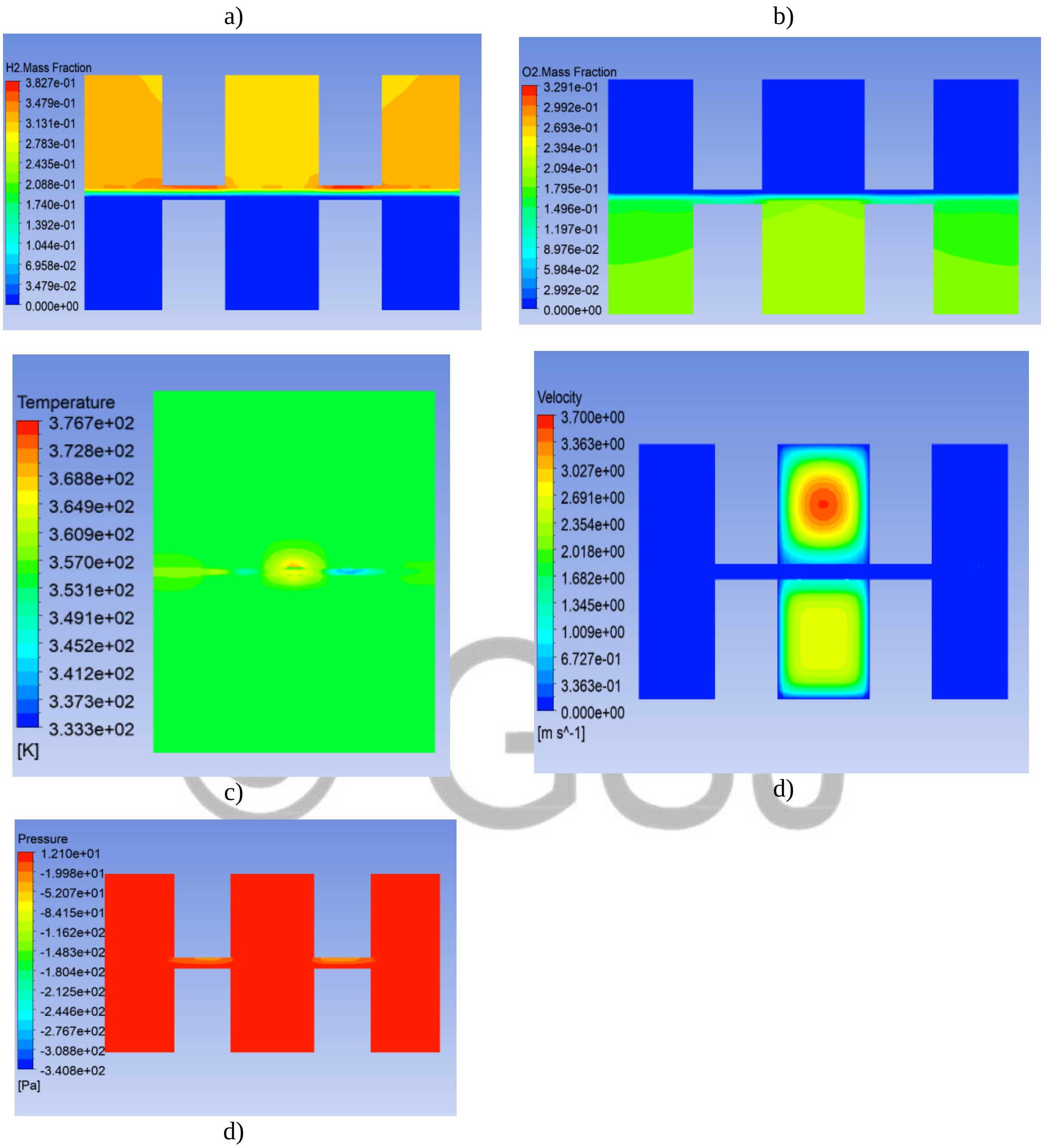


Figure 24. Biometric flow channel a) Distribution of Hydrogen b) distribution of Oxygen c) temperature distribution d) flow velocity d) distribution of Pressure

Conclusion

This paper presents a three-dimensional CFD modeling and simulation to investigate the effects of different flow channels on PEMFC performance. The gas flow channel (GFC) is the crucial part essentially used to distribute the fuel gases on the electrode surface and to remove water as a byproduct. A PEM fuel is made of an anode that accommodates the fuel, a cathode that supplies oxidant, and an electrolyte that separates the two electrodes (anode and the cathode) and provides a passage for the transport of ions. Both electrodes have three distinct components: thus, are the gas diffusion layer (GDL), the gas flow channel, and the catalyst layers.

The flow channel designs used in this study include the straight, serpentine flow channels and biometric flow channels. According to different researchers, Counterflow creates better performance for the fuel cell. Therefore, in this study, we used a cross-flow type of flow channel. Compared to the experimental results, the predicted effects of different flow channel designs on the PEMFC performance demonstrate good agreement. The performance of PEMFC with the serpentine and biometric flow channel is superior to that of PEMFC with the straight flow channel, 73 which is shown in the experiments. This model provides valuable information about the transport phenomena inside the fuel cell such as the distribution of reactant gas concentration, temperature distribution, pressure distribution, flow velocity distribution, and local current density distribution. In addition, based on the calculation results, the performance of the PEMFC gas flow channel is significantly influenced by the different designs of flow channels. The simulation results here give good agreement with experimental results data reported in the literature and the newly designed model. Blockage enhances the net electrical power. At 0.6V experimental current density value is 2.338 A/cm^2, 2blockages (0.8mm and 1mm) 2.231 A/cm^2 and 1.88 A/cm^2 respectively, 2 blocks (0.8mm) 2.231 A/cm^2. At 0.6V the current density value increases from 2.338 A/cm^2 (serpentine) to 2.654 A/cm^2 (Biometric FC). The performance of PEMFC with the Biometric flow channel is superior to that of other PEMFCs.

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