International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 11 Issue: 10 | Oct 2024 www.irjet.net p-ISSN: 2395-0072

EFFECTS OF FLOW CHANNEL ON PERFORMANCE OF PEM FUEL CELL

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Abstract - *The study focused on simulating the flow channels in Polymer Electrolyte Fuel Cells (PEMFC) under different operating conditions to evaluate their effects on the cell performance. Using a three-dimensional model of a PEMFC with a 25cm^2 active area, various flow channel designs (single serpentine, bi serpentine, and tri serpentine) were investigated using ANSYS FLUENT software. The obtained results were compared to the experimental data to validate the model. Factors like pressure distribution, and velocity magnitude were examined alongside fuel cell performance. The findings indicated that the tri serpentine flow channel designs exhibited a power density of 0.6655 W/cm^2 at 373K while the bi serpentine produced 1.10 % lower, and the single serpentine yielded 1.15 % lower than the tri serpentine flow channel*

1.INTRODUCTION

To help create a more sustainable future, advanced technologies such as solar-powered vehicles and Fuel Cell Electric Vehicles (FCEVs) are essential to reduce emissions and address global warming. In automotive applications, Researchers are interested in Polymer Electrolyte Membrane Fuel Cells (PEMFCs) due to their high efficiency, low- temperature operation, high power density, rapid startup, and system durability. The flow channel plays an essential role in PEMFC, facilitating the conveyance of reactants to the electrodes. The efficiency of the transport processes are determined by the design configurations, dimensions, and patterns, which impact the cell's overall performance.

Studies shows that the performance of Polymer Electrolyte Membrane Fuel Cells (PEMFCs) can be modified by adjusting the geometry of the flow channels. Liu et al. [1] developed a computational model to optimize the dimensions of the current collector and the cross-sectional area of the flow channels. The findings revealed that the power output of PEMFCs increased by reducing the total width of the flow channels and the rib-to-total width ratio. Hashemi et al. [2] studied the performance of PEMFCs with serpentine and straight flow fields. The results demonstrated that the serpentine flow fields achieved a more uniform current density and temperature distribution.

Mahammad et al. [3] determined that the performance of PEMFCs are modulated by the channel dimensions, determining that an optimal rib thickness augments efficiency. Yousef et al. [4] explored a Computational Fluid Dynamics (CFD) methodology to investigate the ramifications of novel flow channel design on PEMFC performance, discovering that this innovation design performed better than conventional configurations. According to Liu et al. [5], disparate gas flow field architectures outcomes include pin-type, single, and multiple channels. Iranzo et al [6] utilized a CFD paradigm with ANSYS Fluent software to compare parallel and serpentine flow fields, explaining that serpentine configuration conferred superior performance enhancements. Amirinejad et al. [7] analyzed a PEMFC with an active area of 5cm^2 under assorted operational conditions including temperature, pressure, and reactant gas humidity–demonstrating that an increase in cell temperature and operating pressure enhanced performance. Carcade et al. [8] investigated the impact of channel cross-sectional area and serpentine channel patterns, concluding that minimizing channel and land width while augmenting the number of serpentine channels yielded superior cell performance at elevated current densities.

The research by Santamaria et al [9] involved the distribution of gas in channels ranging from 5cm to 25 cm. It was observed that the longer channels were more effective than the shorter ones. By simulating PEMFCs through the fluent module, Eker and Taymaz [10] investigated the influence of flow channel width and operating temperature. The findings revealed that as the flow channel width increased, the fuel cell performance declined when the temperature dropped. The study by Sukkee and Wang [11] using Computational Fluid Dynamics (CFD) to analyze the 3D interaction between straight and interdigitated flow field channels, revealing that interdigitated flow channel is more efficient at removing water from the catalyst layer than the straight channel. Zhongmin Wan et al. [12] developed a novel M-shaped channel design for PEMFC bipolar plates. The study found that by increasing the height and thickness of obstacles improved reactant flow along the wall, which enhanced heat and mass transfer and yielded a 21.3% higher power density without additional pumping energy.

According to Geneva et al. [13], an extended flow field can lead to pressure loss, contributing to water flooding and negatively impacting PEMFC performance. Shimpalee et al. [14] explored the performance of a PEMFC with an active area of 200 cm^2 incorporating several configurations of Straight Flow Field (SFF). The findings of Mahammad et al.

[15] highlighted that the PEMFC performance is affected by the size of the channels and the optimal rib thickness contributing to better performance. The research by Roshandel et al. [16] examined a bio-inspired flow field design for PEM fuel cells, featuring a leaf-shaped channel. The analysis revealed more uniform distribution of oxygen (O2) concentration, pressure, and velocity distributions than standard flow field designs. The current density increased by 26% over serpentine fields and 56% over parallel fields. By altering the channel depth, Chowdary et al. [17] developed four different flow fields and discovered that a decrease in channel depth improved species diffusion in PEMFCs. The work by Atul Kumar et al. [18] focused on optimizing the flow channel shapes and dimensions in the end plates of the serpentine flow field. It was observed that a 9% increase in hydrogen (H2) consumption at the anode contributed to enhanced performance of the PEMFC.

The primary aim of this investigation is to evaluate the performance of Polymer Electrolyte Membrane Fuel Cells (PEMFCs) by modulating the geometrical parameters of the flow channels under a spectrum of operational conditions. This research encompasses a comparative analysis between extant published data and the author's simulation results. Three novel serpentine flow channel architectures were devised and simulated utilizing the ANSYS FLUENT module across varied operational regimes. Critical performance metrics such as pressure distribution, and velocity magnitudes were analyzed. Additionally, a comparative study was executed by varying the dimensions of the flow channel ribs, subjected to an array of parameters. The outcomes demonstrate that the tri-serpentine configuration manifests superior performance relative to other designs, attributed to its diminished pressure drop. Furthermore, the discourse includes a detailed examination of velocity magnitude as well.

2. MODEL VALIDATION

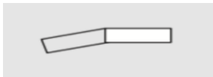
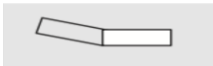
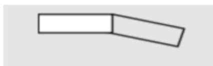
In any Computational Fluid Dynamics (CFD) analysis, validation is a critical aspect. This process involves comparing the simulated data with existing results or experimental data to ensure accuracy and reliability.

In this design, five distinct configurations of the flow channels are examined, integrating both rectangular and slanted channel geometries. To corroborate the fidelity of these models, empirical data sourced from Wawdee P, et al [19] is leveraged for comparative analysis. The intricate dimensions and specifications of the experimental PEMFC are succinctly delineated in Table 1. The arrangements are detailed in Table 2.

Table -1: Details of the experimental PEMFC [19]

S.No	PART NAME	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
1	Anode and Cathode Flow Plate	200	200	10
2	Anode and Cathode Catalyst	173.4	86.5	0.4
3	Anode and Cathode GDL	173.4	86.5	0.4
4	Membrane	173.4	86.5	0.4

Table -2: Details of the various configuration of experimental PEMFC [19]

RUN	ANODE	CONFIGURATION	CATHODE
1	Rectangular Channel Plate (RP)		Rectangular Channel Plate (RP)
2	Down-Slanted (ADS)		Down-Slanted (ADS)
3	Up-Slanted(AUS)		Up-Slanted(AUS)
4	Rectangular Channel Plate (RP)		Rectangular Channel Plate (RP)
5	Rectangular Channel Plate (RP)		Rectangular Channel Plate (RP)

The fuel cell under consideration has an active area of 150 cm^2. Its flow channel plate was designed with parallel serpentine arrangements featuring primary grooved channels. Specifically, rectangular cross-sectional channels measuring 1.5mm in width and 1mm in depth were grooved onto a conventional graphite flow field. In contrast, the modified assisted flow field incorporates channels slanted at an angle of 35°. The simulation encompasses two distinct temperature 353K and 368K, operating at a voltage of 0.5V and 0.7V. The figure 1shows the design of experimental PEMFC.

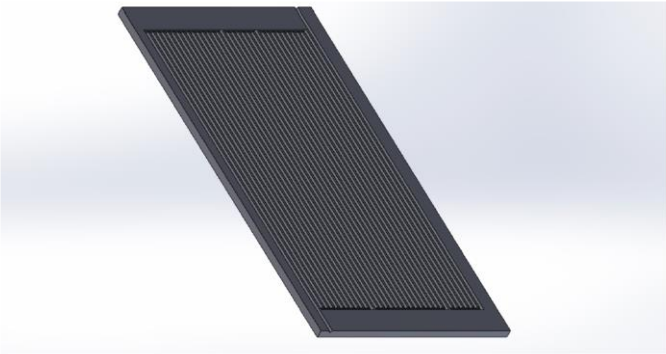


Fig -1: Design of experimental PEMFC

2.1 COMPARISON WITH SIMULATION ANALYSIS

The obtained simulation data were compared with the experimental data. The results were slightly varying from the experimental data. This variation is due to the differences between the experimental circumstances. For example, the software simulation considers that the system occurs with no leakage of the substances whereas the experimental had some leakage issues.

Below is a comparison of data analysis conducted at temperatures of 368K (95°C) and 353K (80°C), both at a voltage of 0.5V and 0.7V, across different configurations.

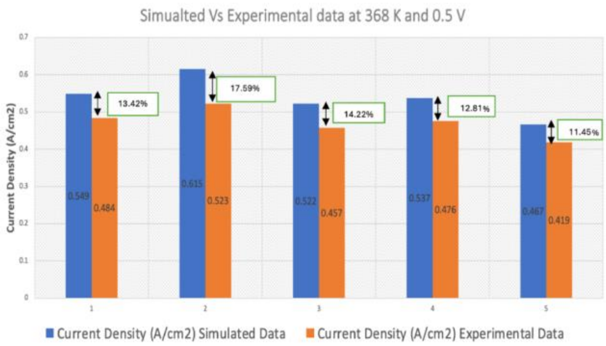


Fig -2: Comparison of simulated and experimental data of PEMFC in 368K temperature at 0.5V voltage

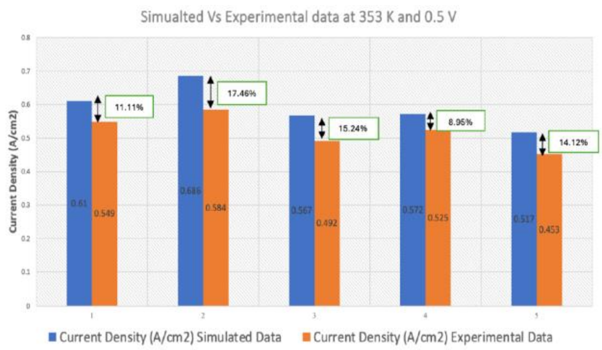


Fig -3: Comparison of simulated and experimental data of PEMFC in 353K temperature at 0.5V voltage

Figures 2 and 3 depict the comparison between simulated and experimental results for all five configurations and the errors were indicated at the top of the graph in each case.

The following presents a comparative analysis of data obtained at 368K (95°C) and 353K (80°C), specifically at 0.7V across different configurations.

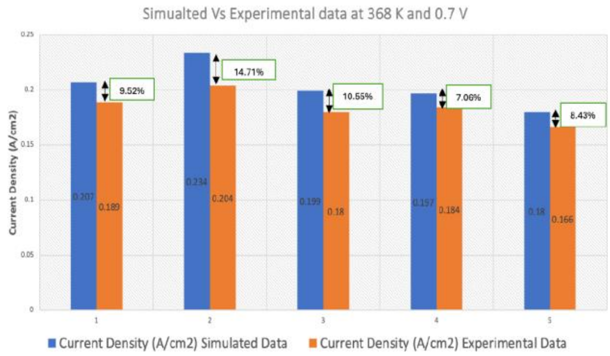


Fig -4: Comparison of simulated and experimental data of PEMFC in 368K temperature at 0.7V voltage

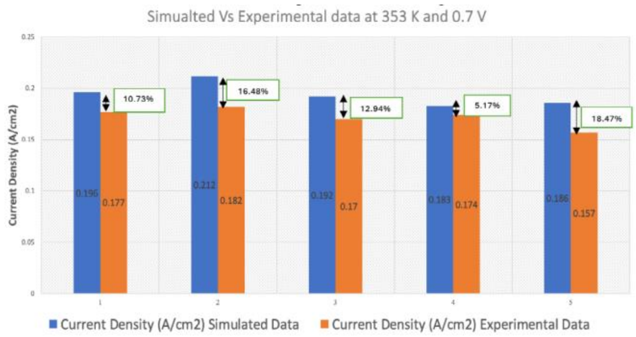


Fig -5: Comparison of simulated and experimental data of PEMFC in 353K temperature at 0.7V voltage

Figures 4 and 5 depict the comparison between simulated and experimental results for all five configurations and the errors were shown at the tips of the bar graphs.

These results indicate the percentage of errors between each configuration's simulated and experimental current densities under the specified operating conditions. The results indicate that the current density is inversely proportional to the circuit's voltage drop, given that other factors remain constant. The simulated data were consistently higher because of no leakage of gaseous substances. The comparison shows that the errors are reasonable.

3. GEOMETRY DESIGN AND SIMULATION MODELING

The geometry model was designed using SOLIDWORKS 2022 software, with specific zones defined for modeling domains like current collectors, flow field channels, gas diffusion layers, catalyst layers, and membranes.

Subsequently, the grid was exported to ANSYS FLUENT 2022 R2 licensed software for meshing and solving the complete module set. ANSYS offers an add-on PEM fuel cell module to solve fluid-based equations like Joule heating, electrochemistry, membrane water transport, multiphase, multi-component diffusion, and anisotropic e-conductivity in porous electrode, Butler-Volmer rate. The numerical model represents a single cell geometry employing humidified hydrogen and air as reactant gases operating temperatures from 313K to 373K, with an operating pressure of 2 bar. The open circuit range from 0.1 V to 1V covering an active area of 5 cm^2 and channel dimensions of 2mm width and depth. Mesh characteristics, geometry properties, and simulation parameters are detailed in table 3,4, and 5 with mesh quality consistently maintained across all designs.

Table -3: The characteristics of the mesh

S.No	DESCRIPTION	VALUES
1	Nodes	1008943
2	Elements	1109348

The corresponding modules necessary for the analysis were selected in the software, including the flow module for species flow based on specified boundary conditions like pressure and velocity, the species transport module for chemical reactions using the diffusivity matrix, and the current distribution module to determine generated and density corresponding to reactions. A coupled analysis of these modules were performed, culminating in the deduction of power density from the polarization curve.

Table -4: The geometric parameters of PEMFC

S.No	PART NAME	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
1	Anode and Cathode Flow Plate	80	80	10
2	Anode and Cathode Catalyst	80	80	0.08
3	Anode and Cathode GDL	80	80	0.3
4	Membrane	80	80	0.127

Table 4 shows the details of the design of PEMFC and the materials used for each component of the cell

Table -5: Operating conditions and relevant parameters of the study [20]

S.No	PARAMETERS	VALUES	REF
1	Cell Temperature (K)	313/323/333/343/ 353/363/373	Estimated
2	Mass flow rate of Hydrogen (H2) at Anode (Kg/s)	$4.33e^{-07}$	[20]
3	Mass flow rate of Oxygen (O2) at Cathode (Kg/s)	$3.33e^{-07}$	[20]
4	Anode inlet temperature (K)	313/323/333/343/ 353/363/373	Estimated
5	Cathode inlet temperature (K)	313/323/333/343/ 353/363/373	Estimated
6	Operating Pressure (Bar)	2	[20]
7	Open Circuit Voltage (V)	0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1	Estimated
8	Porosity of GDL	0.4	Assumed
9	Porosity of CL	0.5	Assumed

3.1 MODELING ASSUMPTIONS

The simulated 3D fuel cell comprises single, bi, and tri serpentine straight channels, as depicted in a figure 6, 7 and 8 respectively. Table 4 provides detailed dimensions, while table 5 outlines the operating conditions and relevant parameters used in the simulation. The model is developed based on specific following assumptions.

• The Polymer Electrolyte Membrane Fuel Cell (PEMFC) is operated under steady-state conditions, maintaining a constant temperature consistent with its operational parameters

• Simulated scenarios utilizing hydrogen and oxygen in their pure form, adhering strictly to the principles of the ideal gas law

- Gas flow within the channel is constrained to the laminar regime, ensuring a predictable and controlled fluid dynamic environment

- The constituent materials of the cell, including catalyst layers, Gas Diffusion Layers (GDLs), and the membrane, are modeled as homogeneous and isotropic entities, essential for accurate simulation results

- The membrane's impermeability to gases is assumed, ensuring no undesirable leakage currents or gas crossover effects

- A uniform mass flow rate is prescribed at the channel inlet, maintaining a consistent and controlled flow of reactants

- The channel outlet is set to a fixed pressure, maintaining equilibrium conditions and ensuring consistency performance evaluations

3.2 DESIGN AND SIMULATION OF FLOW CHANNEL OF PEMFC

The 3 fuel cells with different flow channels are given below. Each fuel cell is varied by the dimension of flow channel. These configurations include a single serpentine flow channel, a bi serpentine flow channel, and a tri serpentine flow channel. Comprehensive design specifications for these Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are provided elaborately in table 4.

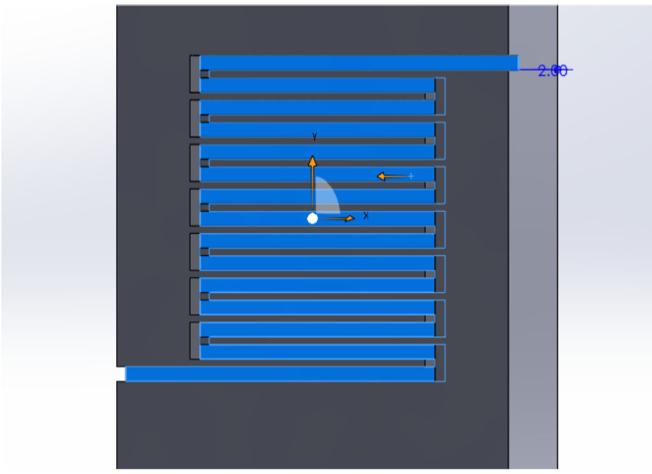


Fig -6: 2mm flow channel width of single serpentine PEMFC

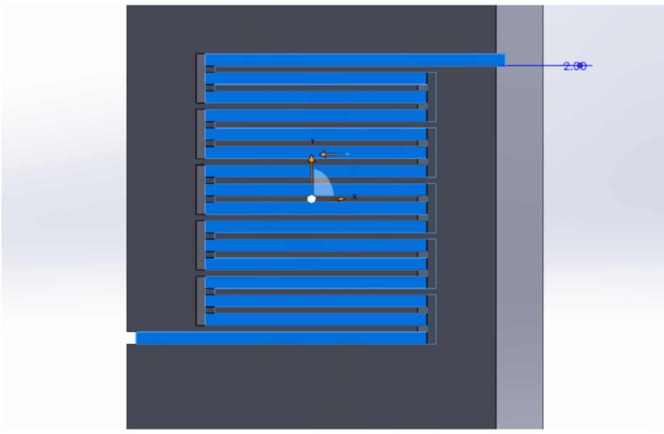


Fig -7: 2mm flow channel width of bi-serpentine PEMFC

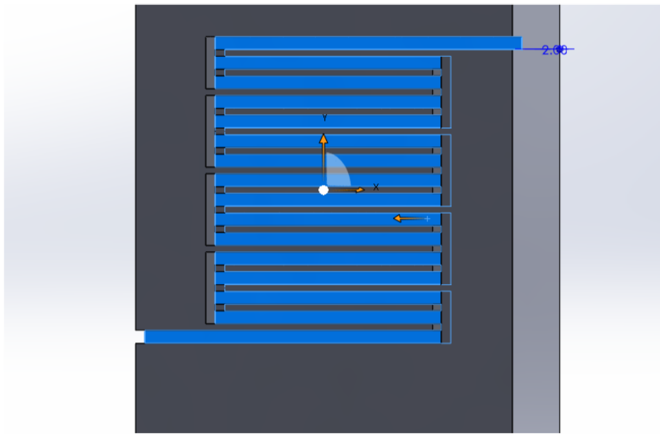


Fig -8: 2mm flow channel width of tri-serpentine PEMFC

All PEMFC's are simulated with active area of 25cm^2 under various parameters which has been mentioned in table 5. The polarization curve graph featuring Voltage (V) along the primary Y-axis, Power Density (W/cm^2) along the secondary Y-axis, and Current Density (A/cm^2) on the X-axis is shown in figure 9. This graph comprises three Voltage-Current (V-I) curves and three Power-Current (P-I) curves each representing the performance of single, bi-serpentine, and tri-serpentine flow channel configurations within the PEMFCs.

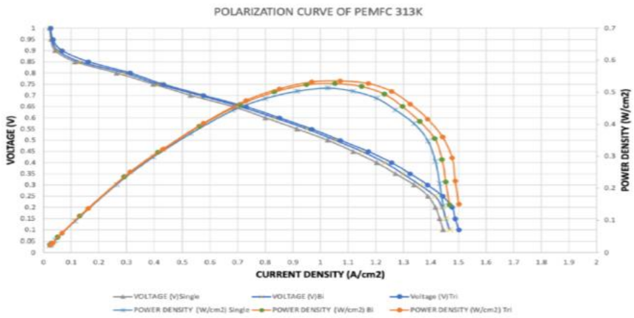


Fig -9: Polarization curve of PEMFC at 313K (40°C) and 2 bar pressure

Figure 9 displays the polarization curve of the PEMFC at 313K (40°C) and 2 bar pressure. In the single serpentine flow channel, the maximum current density is measured at 1.026 A/cm², yielding a corresponding power density of 0.513 W/cm² at 0.5 V. Similarly, in the bi-serpentine flow channel, the maximum current density is recorded as 1.053 A/cm², resulting in a power density of 0.5265 W/cm² at 0.5 V. Lastly, in the tri serpentine flow channel, the maximum current density is determined to be 1.071 A/cm², corresponding to a power density is 0.5355 W/cm² at 0.5 V.

As all polarization curves are similar to figure 9, the results for the rest of the temperatures (323K, 333K, 343K, 353K, 363K, 373K) are shown in tabular format in table 6.

Table -6: Current and Power Density of PEMFC at (323K, 333K, 343K, 353K, 363K, 373K) and 2 bar pressure

S.No	FLOW CHANNEL	TEMPERATURE (K)	VOLTAGE (V)	CURRENT DENSITY (A/cm²)	POWER DENSITY (W/cm²)
1	Single Serpentine Flow Channel	323 (50°C)	0.5	1.053	0.526
2	Bi Serpentine Flow Channel	323 (50°C)	0.5	0.981	0.539
3	Tri Serpentine Flow Channel	323 (50°C)	0.55	1.02	0.55
4	Single Serpentine Flow Channel	333 (60°C)	0.55	0.982	0.54
5	Bi Serpentine Flow Channel	333 (60°C)	0.55	1.007	0.554
6	Tri Serpentine Flow Channel	333 (60°C)	0.5	1.167	0.583
7	Single Serpentine Flow Channel	343 (70°C)	0.55	0.994	0.5467
8	Bi Serpentine Flow Channel	343 (70°C)	0.55	1.03	0.5665
9	Tri Serpentine Flow Channel	343 (70°C)	0.55	1.142	0.6281
10	Single Serpentine Flow Channel	353 (80°C)	0.5	1.131	0.5655
11	Bi Serpentine Flow Channel	353 (80°C)	0.5	1.61	0.5805
12	Tri Serpentine Flow Channel	353 (80°C)	0.5	1.198	0.599
13	Single Serpentine Flow Channel	363 (90°C)	0.5	1.163	0.5815
14	Bi Serpentine Flow Channel	363 (90°C)	0.5	1.194	0.597
15	Tri Serpentine Flow Channel	363 (90°C)	0.55	1.152	0.6336
16	Single Serpentine Flow Channel	373 (100°C)	0.5	1.153	0.5765
17	Bi Serpentine Flow Channel	373 (100°C)	0.5	1.208	0.604
18	Tri Serpentine Flow Channel	373 (100°C)	0.55	1.12	0.6655

3. 3 PRESSUE DISTRIBUTION OF PEMFC

To enhance performance, optimizing pressure distribution is a crucial factor. The simulation is carried out across all three designs of flow channels of PEMFC to understand their impact on pressure distribution. The primary aim is to identify the strategies for improving fuel cell performance through effective pressure management. The pressure distribution of the single serpentine flow channel is shown in figure 10 and table 7 explains the pressure distribution of various configurations of PEMFC. For brevity, the figures of the bi and tri serpentine flow channels were not shown.

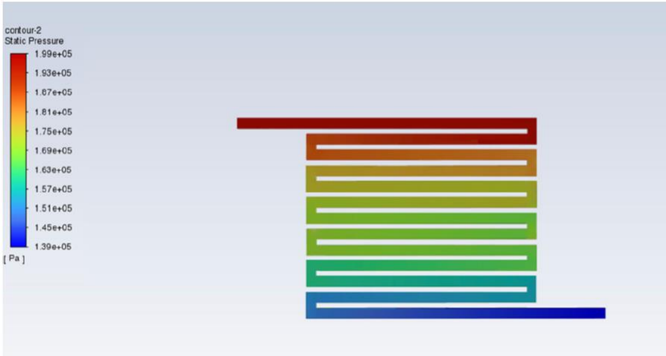


Fig -10: Pressure distribution of 2mm flow channel width of single serpentine PEMFC at 0.5V

Table -7: Pressure distribution of 2mm flow channel width of various configurations of PEMFC

S. No	Flow Channel	Width (mm)	Voltage(V)	Inlet Pressure (kPa)	Outlet Pressure (kPa)	Pressure Difference (kPa)	Corresponding Current Density (A/cm²)
1	Single Serpentine Flow Channel	2	0.5	199	139	60	1.173
2	Bi Serpentine Flow Channel	2	0.5	199	151	48	1.208
3	Tri Serpentine Flow Channel	2	0.55	199	163	37	1.21

Despite variations in pressure drop, it is observed that the pressure is distributed evenly across all designs. The higher pressure drop in the single serpentine flow channel can be attributed to the presence of more bends in its design, leading to increased resistance and consequent pressure drop. Conversely, the tri serpentine design exhibits the minimum pressure drop due to its fewer bends, ultimately contributing to improved cell performance.

3. 4 VELOCITY MAGNITUDE OF THE PEMFC

Velocity magnitude is indeed one of the crucial parameters for assessing the performance of PEMFCs. The velocity magnitude of all the different types of flow channels are discussed below. The velocity magnitude of the bi serpentine flow channel is shown in figure 14 and table 8 explains the velocity magnitude of various configurations of PEMFC. For brevity, the figures of the single and tri serpentine flow channels were not shown.

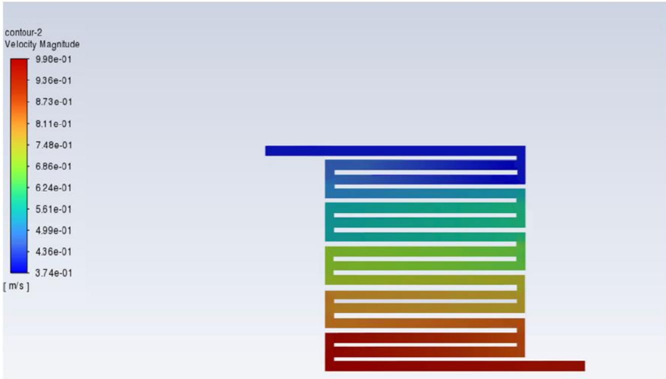


Fig -11: Velocity magnitude of 2mm flow channel width of bi serpentine PEMFC at 0.5V

Table -8: Velocity magnitude of 2mm flow channel width of various configuration of PEMFC

S. No	Flow Channel	Width (mm)	Voltage(V)	Inlet velocity (m/s)	Outlet Velocity (m/s)	Difference in Velocity Magnitude (m/s)	Corresponding Current Density(A/cm²)
1	Single Serpentine Flow Channel	2	0.5	0.514	1.28	0.766	1.173
2	Bi Serpentine Flow Channel	2	0.5	0.374	0.998	0.624	1.208
3	Tri Serpentine Flow Channel	2	0.55	0.267	0.946	0.679	1.21

The velocity magnitude in the single serpentine flow channel is typically higher due to its straighter design, allowing for more direct flow. This configuration often results in efficient transport of reactants and better performance. In the bi serpentine flow channel, the velocity magnitude is slightly lower compared to the single serpentine design. This is due to the presence of additional bends and the flow path, which reduce overall velocity. The velocity magnitude in the tri serpentine flow channel is generally lower than both the single and bi serpentine designs. While this configuration offers increased surface area for reactant contact. Furthermore, it is observed that the velocity is evenly distributed throughout the flow channel, confirming uniform flow distribution across occurs all the regions of the channel.

4. RESULTS AND DISCUSSION

The three models of PEMFC with seven layers namely anode and cathode flow channels, anode, and cathode GDL, anode and cathode catalyst layers, and membrane were operated at different cell temperatures and 2 bar pressure. The PEMFC of all designs with the cell temperatures of 313K, 323K, 333K, 343K, 353K, 363K, and 373 K have been analyzed. In single serpentine flow channel PEMFC, the maximum power density was 0.5765 W/cm^2 obtained corresponding to the cell potential of 0.5V at a temperature of 373K. The corresponding current density was 1.153 A/cm^2. Next, the bi-serpentine PEMFC was simulated. It is found that the maximum power density was 0.604 W/cm^2 obtained corresponding to the cell potential of 0.5V at a temperature of 373K. The corresponding peak current density was 1.208 A/cm^2. Finally, the tri-serpentine was analyzed, and the maximum power density was found to be 0.6655W/cm^2 obtained corresponding to the cell potential of 0.55V at a temperature of 373K. The corresponding peak current density was 1.12 A/cm^2. The findings indicated that the tri serpentine flow channel designs exhibited a power density of 0.6655 W/cm^2 at 373K while the bi serpentine produced 1.10 % lower than tri serpentine and the single serpentine yielded 1.15 % lower than tri serpentine flow channel.

5. CONCLUSION

Among the three flow field configurations studied, the tri serpentine flow channel offers superior performance, making it the optimal choice for applications that require higher power output and efficiency. On the other hand, the single serpentine flow channel experiences significant pressure loss due to the sharp bends, which disrupt the smooth flow of gases, contributing to greater energy loss and increasing fluid resistance, resulting in reduced cell performance. These results illustrate the importance of optimized flow field design to maintain an efficient and durable PEMFC operation.

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