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Analysis of the Effect of RIB Width and Channel Depth Design Modifications on CFD-Based Parallel Type Bipolar Plates for the Application of Proton Exchange Membrane Fuel Cell Stack Singles

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Abstract: The use of large amounts of fossil fuels can pollute the air with significant amounts of carbon monoxide. Proton Exchange Membrane Fuel Cell (PEMFC) is an attractive alternative because it is able to generate high current with low working temperature, fast start-up time, no pollution, and good durability. In PEMFC systems, bipolar plates are one of the main and important components. This component facilitates the reactants to flow through the designed channel. This study aims to modify the parallel-type flow field design on the bipolar plate using CFD simulation in ANSYS, in order to improve the performance of PEMFC. While flowing through the bipolar plate, the reactants diffuse through the gas diffusion layer, thus connecting with the catalyst layer to generate protons and electrons in the anode and water and heat in the cathode through chemical reactions. The results of the study show that the variation of rib width and channel depth has a significant effect on the pressure distribution and hydrogen flow distribution. These findings can contribute to the improvement of flow distribution efficiency and pressure reduction.

Keywords: PEMFC; Bipolar Plate; Rib Width; Channel Depth; Computation Fluid Dynamics (CFD)

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1. Introduction

Fuel cells, especially Proton Exchange Membrane Fuel Cells (PEMFC), are increasing in popularity in line with the global challenge of reducing greenhouse gas emissions and dependence on fossil fuels. PEMFCs offer an efficient and environmentally friendly energy solution, with great potential for integration into a wide range of applications, from transportation to large-scale energy storage. The technology is capable of generating electricity at high efficiency, even under flexible operating conditions, making it an attractive option for a clean energy future. Furthermore, in the context of the accelerating global energy transition, development and innovation in fuel cell design and optimization are critical to ensure that the technology can achieve better performance, lower costs, and larger scale production[1].

PEMFC can convert chemical energy from hydrogen into electricity with high efficiency and low environmental impact. PEMFCs can be used for a variety of purposes, such as vehicle power sources, portable power, and backup generators. In addition, they have many advantages, such as long-term stability, high energy density, and low operating temperature. Although the cost of fuel cells challenges commercialization, research continues to improve the efficiency, durability, and cost of the membranes. This makes PEMFCs a promising source of clean energy in the future[2].

Bipolar plates must have certain characteristics, such as good mechanical strength, corrosion resistance, and high electrical conductivity. Graphite, metals, such as stainless steel and titanium, and composites consisting of polymers and conductive fillers, such as carbon black or graphite, are very commonly used. The specific application and environment in which the PEMFC is used greatly influence the choice of materials[3].

Computational Fluid Dynamics (CFD) is a technique used to simulate fluid flow numerically. By replacing differential equations with numbers, CFD allows for the analysis of complex systems and aids in the visualization of fluid behavior and interactions with solid boundaries. This technique has been used in many fields, such as determining channel rates, architecture, turbines, and automotive design, and will continue to evolve as technology advances[4].

The journal written by Agyekum et al. (2022) PEMFC is updated with a focus on performance improvement, material characterization, and publication growth. Efforts are made to increase the voltage generated and reduce the weight of the cell through innovative designs of flow plates, membranes, and catalysts. In addition, research focuses on the development of membranes with improved ionic conductivity and thermal stability, and has recorded significant growth in PEMFC research publications with an average annual growth rate of 19.35% since 2000, indicating increasing interest in the application of this technology to reduce carbon footprints in various industrial sectors[5].

2. Materials and Experiment Methods

Type of experimental research with the aim of finding correlations between variables. Using the Computer Fluid Dynamics (CFD) approach by simulating parameters through ANSYS software to obtain optimal results from parameter simulations on ANSYS software and direct field trials. The quantitative research method is research based on the philosophy of positivism, which is used to research natural object conditions (as opposed to experiments) where this research is a key instrument, data sampling is carried out purposively and snowball, data collection techniques with triangulation (combination, data analysis is inductive/qualitative)[6].

The object of this study is the bipolar plate in the PEMFC system, the bipolar plate is one of the main and important components. However, the parallel groove pattern has a disadvantage, namely producing water droplets and the serpentine groove pattern with four channels has been proven to improve cell performance and reduce the occurrence of water droplets. The width and height of the channel affect the performance of the PEMFC. Water discharge increases as the channel height decreases, but cell performance also decreases. Cell performance decreases as the channel width increases because lower gas velocities result in less water discharge. This shows better cell performance in smaller channel cross-sectional areas, because it has a higher gas velocity[7].

The sampling method is carried out through CFD simulations carried out 9 times from 9 alternative designs. Then, it will be analyzed based on pressure drop and velocity and one of the most optimal designs will be obtained. In this study uses secondary data. Secondary data is data that has been collected for purposes other than solving the problem being faced from literature, articles, journals, and websites related to the research subject. Statistical analysis is used in this technique to analyze the data and identify relationships between variables. In the case of flow field design in PEMFC, statistical analysis can be used to evaluate the impact of flow line design modifications on the performance of the material. This includes the impact on pressure, flow, and temperature[8].

This study uses a Simulation Method with modeling and algorithms to predict system performance and analyze the impact of design modifications on PEMFC performance. Simulation can be used to evaluate the impact of design modifications on the flow path, pressure, and temperature of the PEMFC. This study uses a CFD approach to simulate hydrogen flow performance. CFD simulations are carried out using ANSYS software. The ANSYS software used in this study is ANSYS 2021 R2. Before performing the simulation, there are several settings for adjustment. Here are the steps to perform a CFD simulation:

1. Run the ANSYS software, namely Workbench 2021 R2.
2. In the Toolbox, double click on Fluid Flow (Fluent).
3. In the Fluid Flow (Fluent) table, there are Geometry, Mesh, Setup, Solution, and Results.
4. Geometry:
   - Right-click on Geometry and select Import Geometry.
   - Then, browse and select the PFF modification design to be simulated (p1-p9).
5. Mesh:
   - Right-click on Mesh and select Edit
   - In the Detail of "Mesh" section Defaults, change the Element Order to Program Controlled and the Element Size to 0.1 mm. The changes of both elements are to determine the accuracy and efficiency of the numerical simulation.
   - In the Quality section, change the Mesh Metric to Skewness which aims to evaluate the quality of the mesh. This metric is very 27 important because the quality of the mesh greatly affects the accuracy and stability of the numerical solution in CFD simulations.
   - On the Mesh Tab, select Face Meshing
   - Select Mesh type then select Inflation and enter the boundary effect as follows

- Layer thickness 0.01
- Max layer
- Expansion ratio 10: 1.2

- Then create a name for each part such as inlet, walls, and electrode
- Go to Setup
- In the Fluent software settings (Fluent Launcher), change the Solver Processes value to 2 and click Start. These settings affect the performance of the ongoing simulation.
- In the Fluent software Setup section, there are several settings, namely:
  - Models
  - Energy (On)
  - Species Transport (On)
- Boundary condition:
  - Inlet velocity 10 m/s
- Initialization
- Run Calculation

Analysis of the influence of parameters such as rib width and channel depth is very important to optimize the design of parallel flow fields in PEMFCs. Minitab is a statistical program that can be used to analyze data and measure how certain parameters affect fuel cell performance. In this study 28, two Channel Width and Channel Depth were used in the 3×3 factorial design method. Each factor has three levels with different values. Therefore, it can be classified as a variable that is not affected by these factors. The following table shows the 3×3 factorial design method:

Table 1. Factorial Design of 3x3 Rib Width and Channel Depth

	0.6	0.8	1
1.1	1.1 and 0.6 (p1)	1.1 and 0.8 (p1)	1.1 and 1 (p1)
1.3	1.3 and 0.6 (p2)	1.3 and 0.8 (p2)	1.3 and 1 (p2)
1.5	1.5 and 0.6 (p2)	1.5 and 0.8 (p2)	1.5 and 1 (p2)

3. Results and Discussion

Subheadings may be used to divide this section. It should provide a concise and precise description of the experimental results, their interpretation, and possible experimental conclusions. The authors should discuss the findings and how they can be interpreted considering previous research and the working hypotheses. The findings and implications should be discussed in the broadest possible context. Future research directions may be highlighted as well.

3.1. Design Results p1-p9

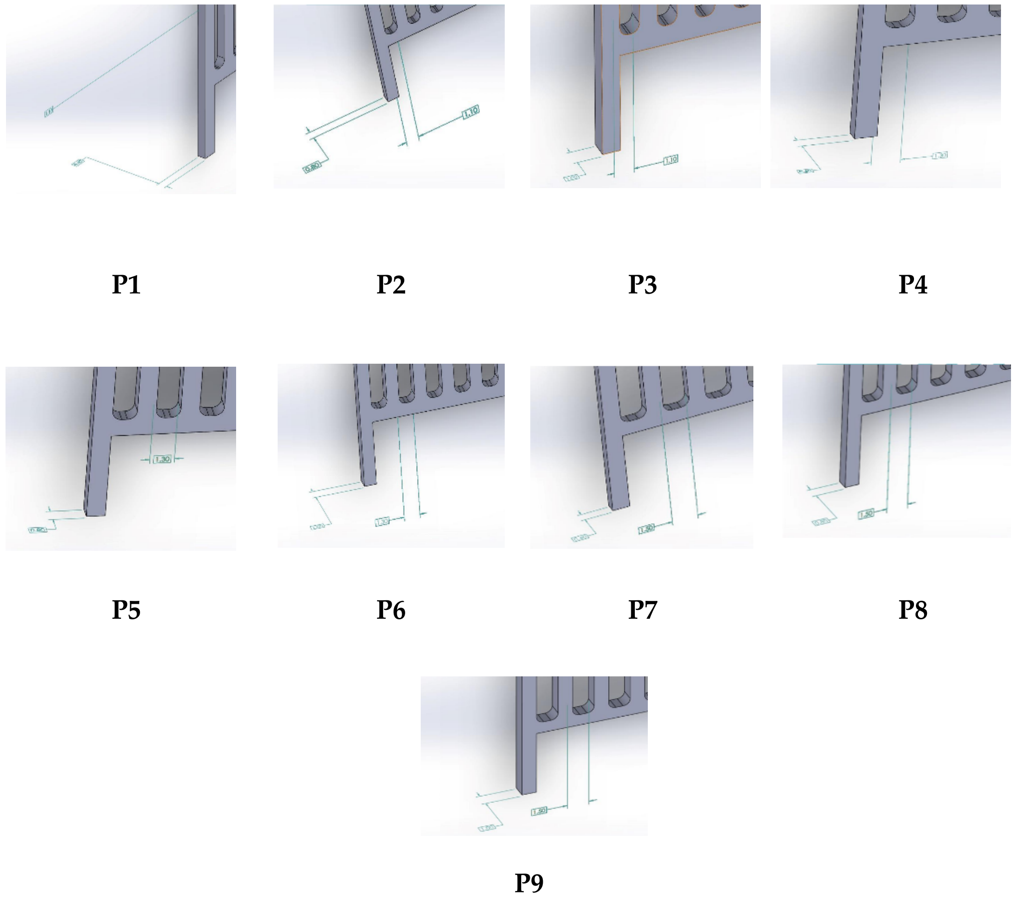


Figure 1. Result of Design P1-P9

Based on Figure 1, the design shown is the result of the application of the 3×3 factorial design method, resulting in 9 combinations or 9 alternative designs by varying the Rib Width and Channel Depth. By setting the Channel Width to 1mm, but the length of the channel from the inlet to the outlet varies. This difference is caused by the variation in the rib width in each design. This variation provides an opportunity to evaluate the performance of each design under different conditions, so that the most optimal design can be selected for the desired application.

Rib width and channel depth greatly affect the pressure drop and flow velocity in Proton Exchange Membrane Fuel Cell (PEMFC) design. Increasing rib width reduces the flow cross-sectional area, causing increased local flow velocity and pressure drop due to higher wall friction. Conversely, increasing channel depth enlarges the space for flow, which reduces flow resistance and lowers pressure drop.

Table 2. Alternative Design Parameters.

Tipe	Rib Width (mm)	Channel Depth (mm)	Channel Width (mm)	Fillet Radius (mm)
P1	1.1	0.6	1	0.5
P2	1.1	0.8	1	0.5
P3	1.1	1	1	0.5
P4	1.3	0.6	1	0.5
P5	1.3	0.8	1	0.5
P6	1.3	1	1	0.5
P7	1.5	0.6	1	0.5
P8	1.5	0.8	1	0.5
P9	1.5	1	1	0.5

But can reduce the flow velocity due to a more even flow distribution. Overall, the right combination of rib width and channel depth is very important to optimize PEMFC performance, because both directly affect the flow distribution and system efficiency[9].

3.1.1. Pressure Drop Calculation

Will be compared with the simulation process in ANSYS software, which will automatically calculate the pressure drop value generated in the geometry model that has been entered. The fluent module will be used for simulation to evaluate the fluid flow that occurs. In the calculation process, reference values are needed as a basis for normal conditions that are entered manually. Reference values include gravity of 9.81 m/s2, pressure of 1 atm, fluid viscosity of 0.8411 (hydrogen gas), and operating temperature of 300K. This process is carried out with 200 iterations until convergent results are obtained. There are a number of data. There are several research variable data that will be used as parameters in calculations with different geometry models as shown in Table 2 The parameters used consist of 3 variations of channel depth and 3 rib width, and this simulation is performed 9 times according to the existing parameters. The researchers used the serpentine line channel type to change 3 different depths and channel lengths[10]. This study uses the parallel channel type because, according to Spiegel's research (2008), the serpentine channel type has a greater pressure drop compared to the parallel flow type[11]. The simulation results will be validated manually by performing theoretical calculations to obtain a pressure drop value that is close to the theory or with a small error rate.

3.2. Simulation and Analysis Results

The simulation results were created using ANSYS 2021 R2 software. This simulation aims to evaluate the design performance in terms of flow distribution and pressure drop. The results obtained will be analyzed and compared with other alternative designs to assess the effectiveness of the changes made.

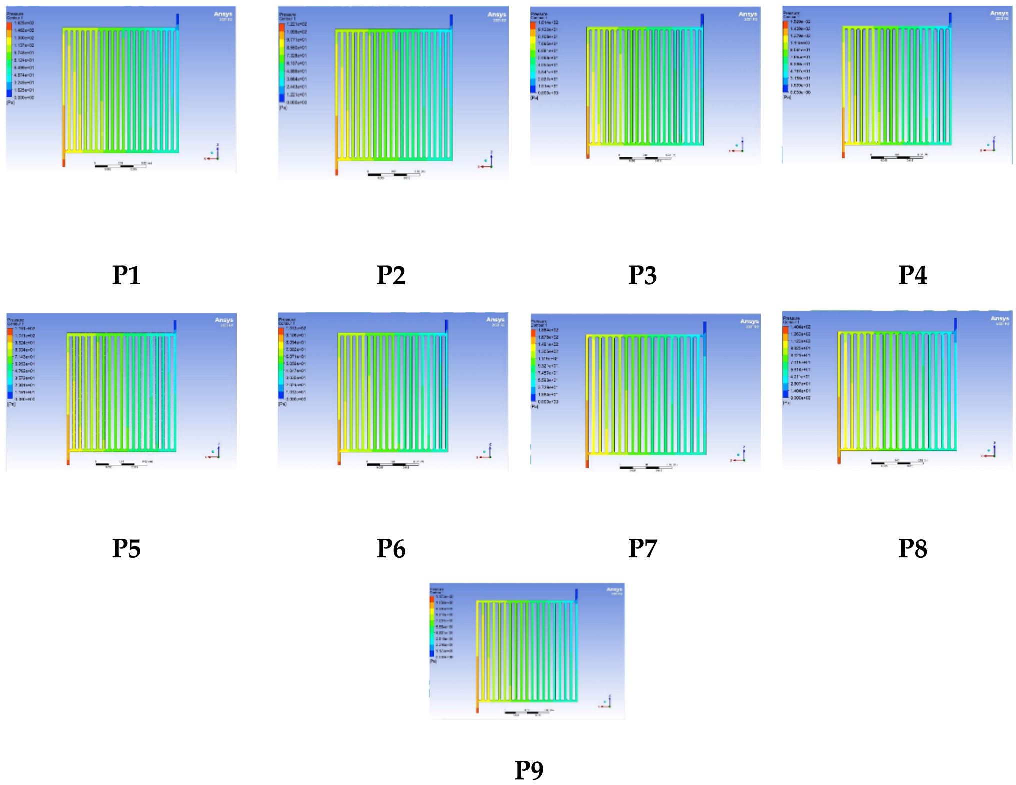


Figure 2. Pressure drop simulation result P1-P9

From the simulation data provided, it can be seen that when the Rib Width increases, the pressure drop also increases. This is especially in the comparison between Rib Width 1.1 mm and 1.5 mm for the same Channel Depth:

- At Channel Depth 0.6mm: Increasing Rib Width from 1.1 mm to 1.5 mm causes an increase in pressure drop from 162 Pa to 186 Pa.

- At Channel Depth 1.0 mm: Increasing Rib Width from 1.1 mm to 1.5 mm increases the pressure drop from 102 Pa to 117 Pa. Increasing Rib Width reduces the effective flow area within the channel, which increases the resistance to fluid flow. With a smaller area, the flow becomes more obstructed, thus causing an increase in pressure drop. However, this can also lead to a more even flow distribution along the channel, although with the penalty of increased pressure drop.

- At Rib Width 1.1mm: Increasing Channel Depth from 0.6 mm to 1.0 mm reduces pressure drop from 162 Pa to 102 Pa.

- At Rib Width 1.5mm: Increasing Channel Depth from 0.6 mm to 1.0 mm reduces pressure drop from 186 Pa to 117 Pa.

As channel depth increases, the volume of the flow chamber increases, which reduces the resistance to flow. This results in a decrease in pressure drop because the fluid can flow more easily through the deeper channel.

3.2.1. Plot Pressure Factorial Results and Analysis

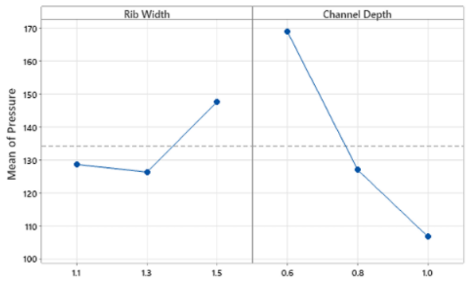


Figure 3. Factorial Plot Pressure

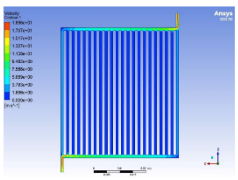
Based on Figure 3 these results show that the difference in Rib Width and Channel Depth factors will greatly affect the pressure drop. At 1.1mm Rib Width the pressure drop rate is relatively low and stable, and for 1.3mm there is a slight decrease in pressure drop compared to 1.1 mm, but it is almost the same. While the Rib Width is 1.5mm Results in a significant increase in pressure drop.

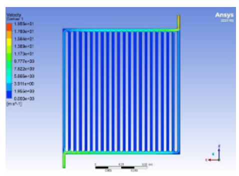
Increased rib width from 1.1 mm to 1.5 mm leads to increased pressure drop. This is due to the decrease in effective flow area when the rib width is larger, increasing fluid flow resistance and cause an increase in pressure drop. At 0.6mm Channel Depth Indicates pressure drop highest, and at 0.8mm there is a significant drop in pressure. Meanwhile, at 1mm the lowest pressure drop can be seen.

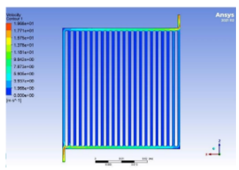
The larger the channel depth, the smaller the pressure drop produced. This can be explained by the increased flow volume that allows the fluid to flow more freely, reduce the resistance and pressure required to move the flow through the channel. The conclusion of the plot is that the 1.1 mm and 1.3 mm rib widths produce a lower and more stable pressure drop compared to the 1.5 mm rib width. and Increase channel depth from 0.6 mm to 1.0 mm significantly reduce pressure drop.

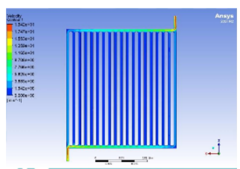
3.3. Simulation and Velocity Analysis Results

Flow rate distribution is an important parameter in bipolar plate performance analysis in PEMFC. A high flow rate can ensure that the reactants are distributed efficiently to the entire surface of the electrode, increasing the effectiveness of the reaction electrochemical. The results of the simulation using ANSYS show hydrogen flow velocity profile in a parallel flow channel has been modified.

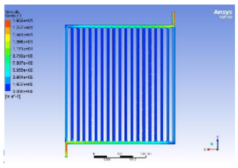








P1 **P2** **P3** **P4**



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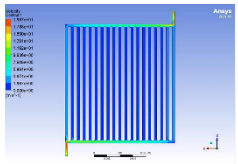

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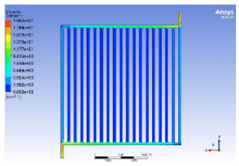

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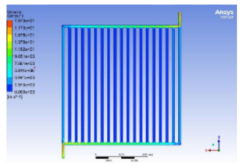

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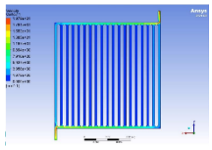

P9

Figure 4. Velocity simulation result P1-P9

From the data provided, we can analyze how the Rib changes Width and Channel Depth affect the flow rate within the channel.

1. Effect of Rib Width

At a Rib Width of 1.1mm and a Channel Depth of 0.6mm, the flow speed is 18.9 m/s while at Channel Depth 1mm the flow speed is increased to 19.6 m/s. While at a Rib Width of 1.3mm with Channel Depth 0.6mm flow rate is 19.4 m/s and at Channel Depth 1mm flow speed increased to 19.9 m/s. And at a Rib Width of 1.5m with a Channel Depth of 0.6mm of flow speed is 19.6 m/s, while with a Channel Depth of 1mm speed The flow increased again to 19.8 m/s. From the simulation data, it shows an increase in ribs width, there is an increase in the flow rate. The following occurs due to the fact that larger rib widths tend to narrow effective area within the channel, which results in increased speed flow to maintain a constant mass flow. However, the change in The flow rate was not very significant between the different rib width variations, suggesting that the rib width had a limited influence at the flow rate in this design.

2. Influence of Channel Depth

At a Rib Width of 1.1mm, an increase in Channel Depth from 0.6 mm to 1.0 mm led to an increase in flow speed from 18.9 m/s to 19.6 m/s produces 0.7 m/s difference increase and achieves a percentage an increase of 3.7%.

Based on the results of the data, Increased channel depth generally increase the flow speed, mainly due to the increase in Channel depth reduces flow resistance. More flow speed high is required to maintain a steady flow of fluid inside deeper channels. Optimal combination of rib width and channel The depth that provides the highest flow speed is found at the rib width 1.3 mm and Channel Depth 1.0 mm, with a flow speed of 19.9 m/s. This indicates that in this design, the channel depth increase has a more significant influence on the flow speed compared to the increased rib width. So that conclusions can be drawn The effect of increasing Channel Depth is more effective in increasing speed flow compared to Rib Width and Design with a Channel Depth that is larger and larger Rib width can provide excellent performance optimal in terms of flow speed, which is important for efficiency gas transportation in PEMFC.

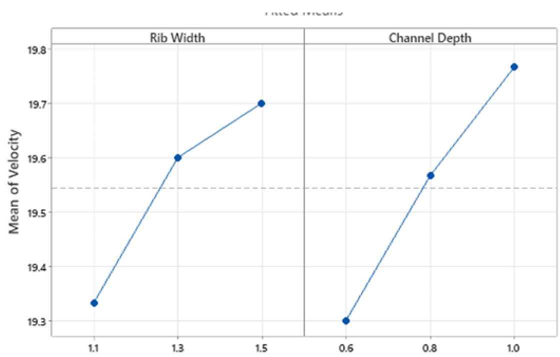

Figure 5. Factorial Plot Pressure

Based on Figure 5 the factorial results of the plot shows when the width of the rib increases from 1.1 mm to 1.3 mm. there is a significant increase in flow velocity. However, when the rib width increases from 1.3 mm to 1.5 mm, the increase in velocity becomes more moderate. This shows that increasing the rib width up to 1.3 mm can effectively increase the flow velocity, but further increases have a smaller impact. Meanwhile, the influence of Channel Depth from the graph shows that increasing the channel depth from 0.6 mm to 1.0 mm causes a significant increase in flow velocity. Larger channel depths (from 0.6 mm to 1.0 mm) tend to provide wider flow paths, thereby increasing the flow velocity. Increasing the rib width from 1.1 mm to 1.5 mm shows that the flow velocity increases, but not as much as the influence of channel depth. Larger rib widths reduce the flow path area, which tends to increase velocity, but the impact is not significant after a certain point. On the other hand, increasing the channel depth from 0.6 mm to 1.0 mm causes a greater increase in flow velocity, because the deeper channel volume allows more fluid to flow with lower resistance. The combination of the two shows that channel depth has a dominant effect in increasing flow velocity compared to rib width.

3.4. Results of Analysis of Variance (ANOVA)

Table 3. Information of Factor.

Factor	Type	Levels	Value
Rib Width (mm)	Fixed	3	1.1 ; 1.3 ; 1.5
Channel Depth (mm)	Fixed	3	0.6 ; 0.8 ; 1

Based on Table 3 shows information about the factors that used for analysis, particularly on experiments involving variations in Rib Width and Channel Depth in the design of parallel flow areas. This information includes two factors, each with three different levels of value. The value is a fixed value if it is categorized as a value remain.

3.4.1 ANOVA based on Pressure

Table 4. Analysis of Variance by Pressure.

Sources	DF	Adj SS	Adj MS	F-Value	P-Value
Rib Width (mm)	2	821.56	410.78	46.80	0.002
Channel Depth (mm)	2	6062.89	3031.44	345.35	0.000
Error	4	35.11	8.78		
Total	8	6919.56			

The very small P-Value (0.002), far below the significance level of 0.05, indicates that rib width has no significant impact on pressure response, as shown by the ANOVA results shown in Table 4. The F-Value of 46.80 indicates that variations in Rib Width are a contributing component but with no significant effect on the simulated system pressure changes. In addition, Channel Depth has a more significant effect on pressure; has a P-Value of 0.000, which indicates a high level of statistical significance, the F-Value of 356.02 indicates that Channel Depth has a more significant effect on pressure.

Table 5. Summary Model by Pressure.

S	R-sq	R-sq (adj)	R-sq (pred)
2.96273	99.49%	98.99%	97.43%

Based on the model summary results in Table 5, this model has proven to be very good at explaining data variations, with an R-sq value reaching 99.49% and an R-sq(adj) of 98.99%. This means that almost all variations in the pressure response can be explained by a model involving channel depth and rib width as factors. In addition, the R-sq(pred) value of 97.43% shows that this model is very effective in predicting pressure for new data. The S value of 2.96273, which is the residual standard deviation, shows that the difference between the observed and predicted values by the model is very small, so the prediction accuracy of this model is very high.

3.4.2 ANOVA based on Velocity

Table 6. Analysis of Variance.

Sources	DF	Adj SS	Adj MS	F-Value	P-Value
Rib Width (mm)	2	0.2156	0.10778	3.66	0.0125
Channel Depth (mm)	2	0.3289	0.16444	5.58	0.070
Error	4	0.1178	0.02944		
Total	8	0.6622			

Based on the ANOVA results in Table 6, it can be seen that Rib Width has a significant effect on the flow velocity response. This is evidenced by the very small P-Value (0.000), far below the significance limit of 0.05. The F-Value of 3.66 confirms that variation in Rib Width is the main factor that significantly affects the velocity changes in the simulated system. In addition, rib width also has a significant impact on flow velocity, with a P-Value of 0.000, indicating a high level of statistical significance. Although its influence is not as large as the channel width, the F-Value of 356.02 indicates that rib width still provides an important contribution to flow velocity variations.

Table 7. Summary Model by Velocity.

S	R-sq	R-sq (adj)	R-sq (pred)
0.171594	82.21%	64.43%	9.6%

Summary Model in Table 7 shows that this model has a very good performance in explaining data variation, with an R-sq value of 82.21% and an R-sq(adj) of 64.43%. This means that almost all variations in speed can be explained by the model that considers rib width and channel depth as factors. However, the R-sq(pred) value of 9.6% indicates that this model is less accurate in predicting speed for new data. In addition, the S value of 0.171594, which is the residual standard deviation, indicates that the difference between the observed value and the predicted value by the model is very small, indicating that the model's prediction is very accurate.

3. Conclusions

Based on the variation of rib width and channel depth in the design of parallel bipolar plates in PEMFC, it has a significant effect on the pressure drop e (pressure drop) and flow velocity. From this, it can be concluded that:

a. Modifications to rib width and channel depth significantly affect hydrogen flow and pressure drop in PEMFC, but channel depth has a greater effect on pressure and velocity compared to rib width. In the development of fuel cell systems for electric vehicles, modification of rib width and channel depth can be optimized to improve hydrogen flow efficiency. In energy storage applications, as well as in industrial applications requiring high power, modification of the bipolar plate design with deeper channel depth can reduce the pressure required for hydrogen flow.

b. From the simulation results, the design with a rib width of 1.3 mm and a channel depth of 1 (p6) mm provides the best balance between high flow velocity (19.9 m/s) and low pressure drop (101 Pa), so it can be considered as the most optimal design for single stack PEMFC applications. The bipolar plate design with 1.3 mm rib width and 1 mm channel depth is ideal for applications requiring a balance between high flow rates and low pressure drop, making it an ideal solution for a wide range of fuel cell applications in the automotive, commercial and heavy equipment industries.

c. The relationship between pressure and channel depth in a Proton Exchange Membrane Fuel Cell (PEMFC) can be summarized as follows is Inverse Relationship, As the channel depth increases, the pressure drop across the channel decreases. This is because a deeper channel provides a larger volume for the fluid to flow through, which reduces flow resistance so increasing the channel depth generally leads to a decrease in pressure drop, facilitating better fluid dynamics within the fuel cell system. And The effect of increasing Channel Depth is more effective in increasing speed flow compared to Rib Width and Design with a Channel Depth that is larger and larger Rib width can provide excellent performance optimal in terms of flow speed, So which is important for efficiency gas transportation in PEMFC.

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