Abstract - This paper is concerned with the optimization of combined effect of various designs and operating parameters with serpentine flow channel of 49 cm² active area affects the performance of the Proton Exchange Membrane (PEM) fuel cell. The fuel cell is an electrochemical device and its performance depends on the flow channel design, number of flow path, channel depth and width, cross section of the flow channel, operating pressure, operating temperature, relative humidity, mass flow rate of the reactant gases and stoichiometric ratio of the reactants. The model, analysis and optimization have done with help of Creo, Ansys CFD and Minitab 17 software respectively. Based on the optimization study, the L: C- 1:2 have produced maximum power density of 0.182 W/cm² and square of response factor (R²) was achieved as 99.84 %.

Keywords- Serpentine flow channel; CFD; Optimization; Design parameters; operating parameters.

I. INTRODUCTION

The energy scarcity and environmental impacts of non-renewable power sources in many countries, focusing on renewable energy source development. The proton exchange fuel cells are environment friendly power source and are suitable for powering both portable devices and mobile application due to its lower operating temperature and high energy density [1]. Chang et al. [2] have examined the effects of channel depths and anode flow rates on the performance of miniature three-pass serpentine flow field design (rib and channel widths were 500 μm and the channel depths were 200, 400 and 600 μm) with the active area of 4 cm² PEMFC. The results showed that the channel depth of 400 μm showed the best results. The cell with lower channel depth provided more flow rate compared with higher channel depth. This was due to higher flow rate giving sufficient pressure to force the reactant to flow through small cross-sectional area. Whereas more channel depth does not require a higher pressure to force the reactant to pass through channels. Instead, high flow rate excessively increases flow velocity, which upsets the water balance in MEA and decreases cell performance. Oosthuizen et al. [3] studied the air flow in a simplified model of the serpentine flow channels with a square cross-section and adjacent diffusion layer on the performance of the PEMFC. The results indicated that the flow crossover does have a significant influence on the pressure variation through the channel, tending to decrease the pressure drop across the channel. There can be crossover of air through the porous diffusion layer from one part of the channel to another due to the pressure drop along the flow channel. Wu et al. [4] integrated the neural network and Taguchi technique for parametric analysis with various parameters like operating temperatures, cathode and anode humidification temperature, operating pressure, and reactant flow rate for the enhancement of PEMFC performance. The results indicated that among the various parameters, temperature and pressure were the major factors to influence the PEMFC performance. A three dimensional computational fluid dynamics (CFD) model was used to investigate the effects of serpentine flow channel curvature and length, pressure drop, velocity distribution on the performance of PEMFC by Jaruwasupant &
Khunatorn [5]. The result revealed that the sharp curve was the best configuration because it has non-uniform flow distribution with low velocity and high pressure drop during the reactant flow.

Vazifeshenas et al. [6] investigated the compound flow field design along with serpentine and parallel designs were verified by using CFD software. The results showed that the parallel flow field revealed weaker performance in comparison to the other two flow fields (compound and interdigitated). The main reason is due to insufficient distribution of the reactants. Optimization of operating and design parameters such as pressure, temperature, stoichiometric ratio of inlet reactant mass flow rate and various landing to channel width on serpentine flow channel of 16 cm² active area of the PEMFC was studied by lakshminarayanan et al [7]. The results were concluded that, the L: C- 1:2 has maximum power density of 0.422 W/cm² and square of response factor (R²) was achieved by Taguchi method as 97.90 %. The effect of the various parameters with various rib to channel width of (L: C) 1:1, 1:2 and 2:2 Multipass serpentine flow channel PEM fuel cell with 36 cm² (6cm x 6cm) active area was analyzed numerically by lakshminarayanan et al [8]. The results revealed that the maximum power densities were obtained as 0.658, 0.642 and 0.596 W/cm² for the L: C of 1:1, 1:2 and 2:2, respectively. However, operating parameters such as pressure, temperature and inlet mass flow rate of reactants influenced the performance of PEMFC considerably. The PEM fuel cell performance has been influenced by operating parameters (pressure, cell temperature, relative humidity and the stoichiometric ratio of reactants) and the design parameters (rib to channel width ratios, depth of the channel and number of passes on the flow channel). Equal current distribution must be ensured through uniform velocity distribution of the reactants at the flow channel. Otherwise, parasitic current may be occurred due to potential differences. The cell temperature must be kept uniform so that the heat produced by electrical resistance and electrochemical reactions must be removed from the cell addressed by Atilla Bıyıkoglu [9].

Kanani et al. [10] investigated the effects of operating conditions on serpentine flow channel for the performance of the PEM fuel cell by using Design of Experiments. Response surface methodology was used to model the relationship between cell potential and power with various operating input parameters. The results revealed that the low and high stoichiometry of reactant on anode and cathode cause the minimum cell power. Whereas the optimum ranges of stoichiometry of fuel and oxidants on anode and cathode leads to the best performance. It is clearly indicated that immediate attention is required for optimizing the simultaneous influence of operating and design parameters for the performance of the PEM fuel cell. Hence this paper has a detailed study about the optimization of operating pressure, temperature, stoichiometric ratio of inlet reactant mass flow rate and various landing to channel width (L:C)-1:1,1:2,2:1&2:2 on serpentine flow channel of 49 cm² active area of PEM fuel cell are to be studied and influence their performance are compared.

II. MODEL DEVELOPMENT

The 49 cm² active area with serpentine flow channel of various landing to channel width configurations were created by Creo Parametric 2.0 as shown in Fig.1.
The modeling was done by creating all individual parts of the PEM fuel cell and the dimensions of individual parts as shown in the Table 1. The various geometrical models (L:C-1:1, 1:2, 2:1 and 2:2) of serpentine flow channel were meshed by using ICEM 14.5. After geometry modeling, discretization of PEM fuel cell was done by ANSYS 14.5 ICEM software. Split block method used for blocking, body fitted mesh was used and projection factor was set to 1. The projection factor determines how closely the edges of the mesh match up with the grid. The Cartesian grid meshing method was used, which is used in the formation of hexahedral mesh to attain accurate results. The simulation of PEM fuel cell was solved by simultaneous equations like conservation of mass, momentum, energy, species concentration, butler–Volmer equation, Joule heating reaction and the Nernst equation to obtain reaction kinetics. The model used to consider the system as 3-D, steady state and inlet gases as ideal condition, system as an isothermal and flow as laminar, fluid as incompressible, thermo physical properties as constant and the porous GDL, two catalyst layers and the membrane as an isotropic.

**Table 1. Assigning dimensions and zone type of fuel cell**

| S.No | Part Name                        | Width (mm) | Length (mm) | Thickness (mm) | Zone type |
|------|----------------------------------|------------|-------------|----------------|-----------|
| 1    | Anode & Cathode Flow channel     | 70         | 70          | 10             | Solid     |
| 2    | Anode & Cathode catalyst         |            | 70          | 0.08           | Fluid     |
| 3    | Membrane                         |            |             | 0.127          | Fluid     |
| 4    | GDL anode & cathode              |            |             | 0.3            | Fluid     |
Taguchi method has been used to find out the most optimum combination among the input parameters which would result in getting the maximum possible output which cause the performance enhancement of PEM fuel cell. In Taguchi method L16 standard orthogonal array with 4-level and 4 factors was used and the parameters were considered as low, high and medium range values. When this orthogonal array was used, significance of factors and optimum combination can be found in 16 runs itself. The factors considered for the analysis were landing to channel width ratios on serpentine flow field design (L: C-1:1, 1:2, 2:1 and 2:2), pressure (1, 1.5, 2 and 2.5 bar), temperature (313, 323, 333 and 343 K), anode and cathode reactants as stoichiometric ratios (S/F) of 3, 3.5, 4 and 4.5. The theoretical value of hydrogen in the anode side was 4.33E-07 kg/s and oxygen in the cathode side was 3.33E-06 kg/s. A control volume approach based on commercial solver Fluent was used to solve the various governing equations. Three-dimensional, double precision and serial processing were used for this model. The species concentration on anode side of H₂, O₂, and H₂O were 0.8, 0, and 0.2 respectively. Similarly, on the cathode side were 0, 0.2 and 0.1 respectively. The Anode and Cathode reference current density was set to be 10000 A/cm² and 20 A/cm² respectively 0.1 kmol/m³ was set to anode and cathode reference concentration, Anode and cathode exchange coefficient was set to be 2. The Reference diffusivity of H₂, O₂ and H₂O was set to as 3E-5. The porosity at anode and cathode side was 0.5. Open circuit voltage was set at 0.95 V on the cathode and the anode was grounded. The cathode voltage has been varied from 0.05 V to 0.95 V used for solving kinetics reaction in order to get the current flux density, H₂, O₂, and H₂O fractions along with the flow field design. Multigrid settings were modified as F-Cycle for all the equations and entered termination restriction value was set as 0.001 for H₂, O₂, H₂O and water saturation. The electric and proton potential values were set at 0.0001. Stabilization method BCGSTAB was selected for H₂, O₂, H₂O, water saturation, electric and proton potential.

III. RESULTS AND DISCUSSION

As per L16 orthogonal array, the inputs were given to the Ansys CFD Fluent analysis software and having all other parameters constant. The power densities for all 16 runs, obtained from analysis CFD software and the corresponding Signal/Noise (S/N) ratios were found from MINITAB 17 software as shown in the Table 3. The landing to channel width ratio of 1:1 for serpentine flow field has shown maximum power densities of 0.171 W/cm² and minimum power densities of 0.124 W/cm² respectively. Similarly for L:C of 1:2 and 2:1 having maximum power density of 0.182 W/cm² and 0.139 W/cm² respectively.

| Run | L:C  | Pressure | Temperature | Stoi.Ratio | Power Density (W/cm²) | S/N Ratio |
|-----|------|----------|-------------|------------|-----------------------|----------|
| 1   | 1x1  | 1        | 323         | 3          | 0.12393405            | -18.1362 |
| 2   |      | 1.5      | 333         | 3.5        | 0.13966125            | -17.0798 |
| 3   |      | 2        | 343         | 4          | 0.15639525            | -16.1155 |
| 4   |      | 2.5      | 353         | 4.5        | 0.1713375             | -15.3230 |
| 5   |      | 1        | 333         | 4          | 0.1511991             | -16.4090 |
| 6   |      | 1.5      | 323         | 4.5        | 0.1392876             | -17.1218 |
| 7   |      | 2        | 353         | 3          | 0.18179325            | -14.8084 |
| 8   |      | 2.5      | 343         | 3.5        | 0.1753416             | -15.1223 |
| 9   |      | 1        | 343         | 4.5        | 0.12438405            | -18.1047 |
| 10  |      | 1.5      | 353         | 4          | 0.13931235            | -17.1202 |
| 11  |      | 2        | 323         | 3.5        | 0.10924875            | -19.2317 |
| 12  |      | 2.5      | 333         | 3          | 0.12273075            | -18.2209 |
| 13  |      | 1        | 353         | 3.5        | 0.1703232             | -15.3745 |
The minimum power densities for the same L:C ratios have 0.139 W/cm² and 0.109 W/cm² respectively. For the landing to channel width ratio of 2:2 has shown maximum and minimum power density of 0.170 W/cm² and power density of 0.142 W/cm² respectively. The optimization was performed for “Larger the Better” type of Taguchi method because power output of PEM fuel cell must be maximized. The S/N ratio plot for the same were obtained using MINITAB 17 software and the corresponding maximum S/N ratio gives better performance as analyzed based on larger the better as shown in the Fig.3. The percentage deviation from maximum to minimum power density of various landing to channel width ratio has found as 38.25, 30.52, 27.52 and 20 respectively.

![Main Effects Plot for SN ratios](image)

**Fig. 3. Mean S/N ratio plot for L:C (A1-A4), Pressure (B1-B4), Temperature (C1-C4), Stoi.Ratio (D1-D4)**

It was concluded from the Fig. 3 that the design parameter such as, landing to channel ratio of serpentine flow channel having L:C-1:1 as A1, and the operating parameters like pressure - 2.5 bar as B4, temperature - 353 K as C4, Stoichiometric ratio of inlet mass flow rate - 4 as D3 were the optimum parameters to show the better PEM fuel cell performance. Delta value of each factor available from the MINITAB 17 software itself was shown in Table 4. The optimization results of various parameters were based on S/N ratios and the significance of each factor by ranking them according to their performance. The factor with highest delta value indicates higher significance factor. It was found that landing to channel width ratio was the predominant factor affecting the performance of PEM fuel cell followed by the other parameters as operating temperature, pressure and stoichiometric ratio of inlet mass flow rate respectively.
### Table 4. Delta and Rank for each level factors of the parameters

| Factors                | Level 1 | Level 2 | Level 3 | Level 4 | Delta | Rank |
|------------------------|---------|---------|---------|---------|-------|------|
| Landing to Channel width (L:C) | -16.66  | -15.87  | -18.17  | -16.02  | 2.3   | 1    |
| Pressure (bar)         | -17.01  | -16.72  | -16.58  | -16.41  | 0.6   | 3    |
| Temperature (K)        | -17.87  | -16.97  | -16.22  | -15.66  | 2.21  | 2    |
| Stoi. Ratio            | -16.68  | -16.7   | -16.66  | -16.68  | 0.05  | 4    |

### IV. CONCLUSION

The maximum power density of optimizing the four different parameters on serpentine flow channel of 49 cm² active area of PEM fuel cell using optimization technique provides 0.182 W/cm² from L:C-1:2 with 2 bar operating pressure, 353 K temperature and 3 stoichiometric ratio of inlet reactant gases and R² value was arrived 99.84 %. The maximum to minimum percentage of power deviation in 49 cm² serpentine flow channel has been found to be 66. The performance of PEM fuel cell with various design and operating parameters has been affected significantly.

### REFERENCES

1. A.P. Manso, X. Garikano, M. Garmendia Mujika. ‘Influence of geometric parameters of the flow fields on the performance of a PEM fuel cell. A review’ Int. J. Hydrogen Energy, 37, 2012, 15256-15287.
2. Cheng, S-J, Miao, J-M & Wu, S-J 2012, 'Investigating the effects of operational factors on PEMFC performance based on CFD simulations using a three-level full-factorial design', Renewable Energy, vol. 39, no. 1, pp. 250-260.
3. Oosthuizen, P, Sun, L & McAuley, K 2005, 'The effect of channel-to-channel gas crossover on the pressure and temperature distribution in PEM fuel cell flow plates', Applied Thermal Engineering, vol. 25, no. 7, pp. 1083-1096
4. Wu, S-J, Shiah, S-W & Yu, W-L 2009, 'Parametric analysis of proton exchange membrane fuel cell performance by using the Taguchi method and a neural network', Renewable Energy, vol. 34, no. 1, pp. 135-144
5. Jaruwasupant, N & Khunatorn, Y 2011, 'Effects of difference flow channel designs on Proton Exchange Membrane Fuel Cell using 3-D Model', Energy procedia, vol. 9, pp. 326-337.
6. Vazifeshenas, Y, Sedighi, K & Shakeri, M 2015, 'Numerical investigation of a novel compound flow-field for PEMFC performance improvement', International Journal of Hydrogen Energy, vol. 40, no. 43, pp. 15032-15039.
7. Lakshminarayanan V, Bala Karthick KS. Optimisation of 16cm² Single Pass Serpentine Flow Channel of PEMFC Using Taguchi Method’, International Journal of Theoretical and Applied Mechanics., 2017, 12, ; 523-532.
8. Lakshminarayanan V, Karthikeyan P, Kiran Kumar DS and Dhilip Kumar SM K. Numerical analysis on 36cm² PEM fuel cell for performance enhancement, ARPN Journal of Engineering and Applied Sciences, 2016, 11, no. 2.
9. AtillaBaykoglu. Review of proton exchange membrane fuel cell models, International Journal of Hydrogen Energy,2005, 30, 1181 – 1212.
10. Kanani H, Shams M, Hasheminasab M & Bozorgnezhad A .Model development and optimization of operating conditions to maximize PEMFC performance by response surface methodology, Energy Conversion and Management,2015, vol. 93; 9-22.