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# Optimization of 16cm$^2$ active area on interdigitated flow channel of PEM fuel cell

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**Abstract :** The Proton Exchange Membrane Fuel Cell (PEMFC) is an electrochemical device and its performance depend on the flow channel design, number of flow path, channel depth and width, cross section of the flow channel, operating pressure ,temperature, relative humidity ,mass flow rate of the reactant gases and stoichiometric ratio of the reactants. In this paper, optimization of operating and design parameters on interdigitated flow channel of 16 cm$^2$effective area of the PEM fuel cell was considered. Creo Parametric 2.0 software used for modeling and CFD Fluent 14.5 software packages used for analysis of PEM fuel cell. The optimization was done by Taguchi method using Minitab 17 software. Based on the optimization study, the R: C- 1:1has maximum influence on PEM fuel cell performance and square of response factor ($R^2$) was achieved by Taguchi method as 95 %.
**Keywords :** Interdigitated flow channel; Taguchi method; Optimization; Design parameters; operating parameters.

## I. Introduction

Fuel cells are converting chemical energy of fuels (hydrogen and oxygen) directly into electricity without any intermediate stage like classical combustion of two and four stroke engine. It has become an integral part of alternative energy sourceswith high energy efficiency without affecting the environment. Among all types of fuel cells, the proton exchange membrane (PEM) fuel cell has reached important stage, particularly for mobile and portable applications. Besides their high-power producing capability, PEM fuel cells work at low temperatures, produce only water and heat as byproduct, and can be compactly assembled, making it as one of the leading candidates for the next generation power generator [1].The PEM fuel cell consists of polymer solid electrolyte membrane placed between an anode and cathode. However, water and heat is the by-product of electrochemical reaction and water accumulation on cathode side due to partial pressure of water vapour condensation. The water management of PEM fuel cell has become an important task, whereas more water accumulation causes “flooding” or less water causes dryness of membrane can adversely affect the performance and lifetime of PEM fuel cells. Water accumulation leads the fuel cell performance unpredictable and unreliable under the nominally identical operating conditions. In order to enhance the performance and reliability of PEMFC, it is important to know more about the mechanism which causes performance lossof PEM fuel cell addressed by Owejan et al. [2] and Nattawut Jaruwasupanta & Yottana Khunatorna [3].

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 cm$^2$ active area of the PEMFC was studied by lakshminarayanan et al [4].The results were concludedthat, the L: C- 1:2 has maximum power densityof0.422 W/cm$^2$ and square of response factor ($R^2$) 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 $cm^2$ (6cm x 6cm) active area was analyzed numerically by lakshminarayanan et al [5].The resultsrevealed that the maximum power densities were obtained as 0.658, 0.642 and 0.596 W/$cm^2$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 ofreactants influenced the performance of PEMFC considerably.

The performance enhancement of the combined effect of design and operating parameters of serpentine and interdigitated flow channel with 25 cm2 active area of PEM fuel cell with four different parameters using optimization technique and CFD carried out by Lakshminarayanan and Karthikeyan [6]. The results revealed that the peak power density of interdigitated flow channel with landing to channel width (L:C)1:2 showed better than the serpentine flow channel with L:C-1:2. 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 [7]. The maximum power density corresponding to Taguchi calculations were in good agreement with analysis software results indicating the compatibility of Taguchi method for PEMFC applications said by Sheng-Ju Wu et al [8].

The effects of interdigitated flow channel with traditional flow channel, the effects of the flow area ratio and the baffle-blocked position of the interdigitated flow field on the performance of PEMFCwere examined experimentally by Yan et al [9]. The results concluded that, the cell performance can be enhanced with an increased inlet flow rate of reactant and cathode humidification temperature. The interdigitated flow fields have better performance than conventional flow field design. Also the results showed that the interdigitated flow field has larger limiting current density, and the power output was about 1.4 times than the conventional flow field. 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. The Taguchi method (orthogonal array $L_9$ -$3^4$) was applied to determine optimum working parameters to obtain the maximum power density of a PEMFC has been investigated by Kaytakoglu and Akyalçın [11]. They concluded that the optimum working conditions were found to be 5 bar of system pressure, 75$^\circ$C of cell and humidifier temperature and 0.5 flow rate ratios of $O_2$ and $H_2$. They, also concluded that the pressure and humidification temperature were the effective parameters on PEMFC performance.

It is clearly indicated that immediate attention is required foroptimizing 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 rib to channel width (R:C)-1:1,1:2,2:1&2:2 on interdigitated flow channel of 16 $cm^2$ active area of PEM fuel cell are to be studied and influence their performance are compared.

## II. Model Development

Three dimensional (3-D) PEM fuel cell model with interdigitated flow channel of various rib to channel width configurations were created by Creo Parametric 2.0 as shown in Fig.1.

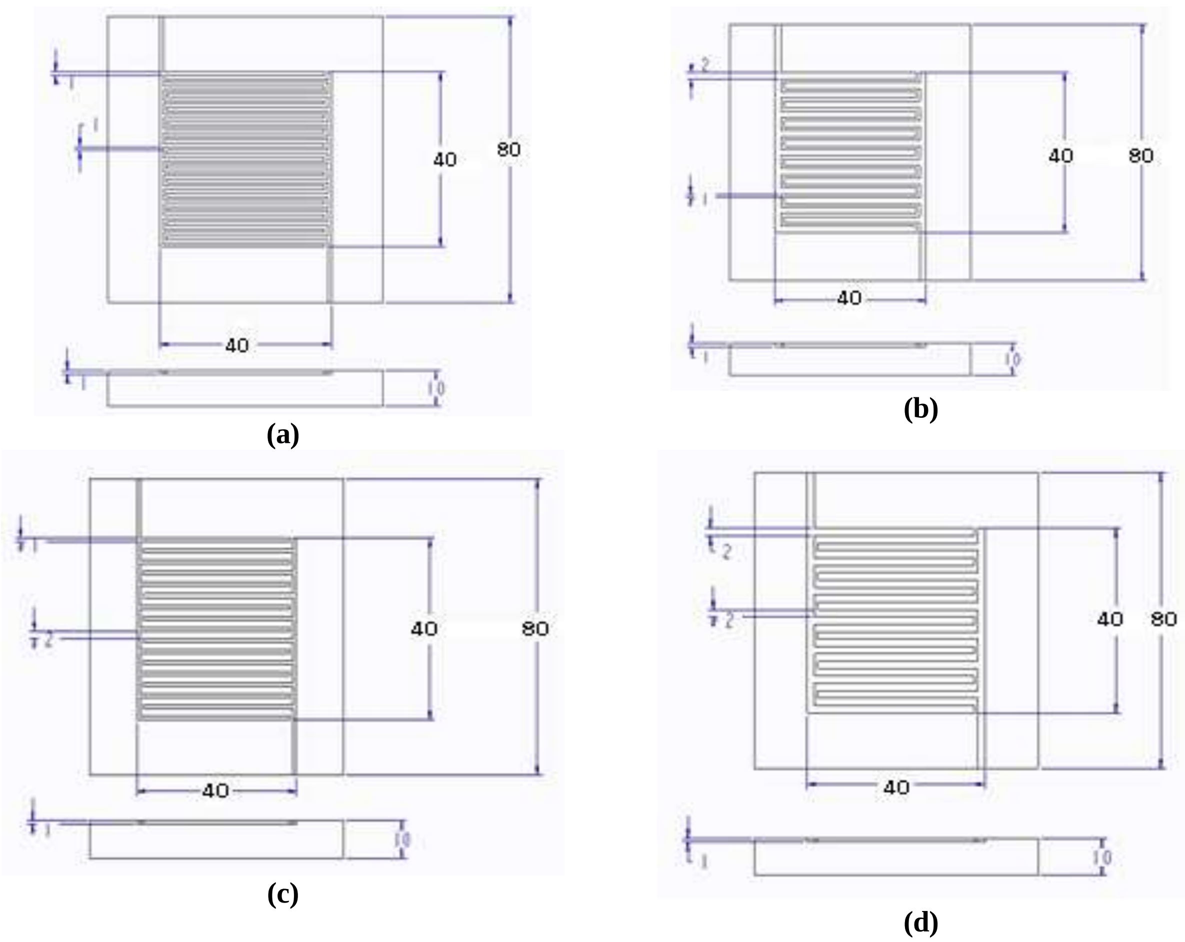


**Fig.1.Various rib to channel width (R: C) (a)1:1 (b)1:2 (c)2:1 and (d)2:2 of interdigitated flow channel of 16 cm$^2$ active area of PEM FUEL CELL**

The modeling was done by creating all individual parts of the PEM fuel cell and the dimensions of individual parts such as the anode and cathode GDL, solid polymer electrolyte membrane, the anode and cathode catalyst layers as shown in the Table 1. The various geometrical models (R: C-1:1, 1:2, 2:1 and 2:2) of interdigitated flow channel were meshed by using ICEM 14.5 (a module of Ansys 14.5).

**Table 1.Dimensions and Zone type, assigning of fuel cell**

| S.No | Part Name | Width (mm) | Length (mm) | Thickness (mm) | Zone type |
|---|---|---|---|---|---|
| 1 | Anode & Cathode Flow channel | | | 10 | Solid |
| 2 | Anode & Cathode catalyst | | | 0.08 | Fluid |
| 3 | Membrane | 40 | 40 | 0.127 | Fluid |
| 4 | GDL anode & cathode | | | 0.3 | Fluid |

After geometry modeling, the next step was discretization of PEM fuel cell done by ANSYS 14.5 ICEM software. The Cartesian grid meshing method was used, which is used in the formation of hexahedral mesh to attain accurate results. 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 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.

A control volume approach based on commercial solver FLUENT 14.5 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 $H_2$, $O_2$, and $H_2O$ were 0.8, 0, and 0.2 respectively. Similarly, on the cathode side were 0, 0.2 and 0.1 respectively. 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, $H_2$, $O_2$, and $H_2O$ 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 $H_2$, $O_2$, $H_2O$ and water saturation. The electric and proton potential values were set at 0.0001. Stabilization method BCGSTAB was selected for $H_2$, $O_2$, $H_2O$, water saturation, electric and proton potential. The Anode and Cathode reference current density was set to be10000A/cm$^2$and 20 A/cm$^2$ respectively 0.1 kmol/m$^3$ was set to anode and cathode reference concentration,Anode and cathode exchange coefficient was set to be 2.The Reference diffusivity of $H_2$,$O_2$ and $H_2O$ was set to as 3E-5.

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 rib to channel ratios on interdigitated flow field design (R: 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.

## 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 software and the corresponding Signal/Noise (S/N) ratios were found from MINITAB 17 software as shown in the Table 3.

The rib to channel width ratio of 1:1 for interdigitated flow field has shown maximum power densities of 0.448 W/cm$^2$ and minimum power densities of 0.350 W/cm$^2$respectively. Similarly for R:C of 1:2 and 2:1 having maximum power density of 0.436 W/cm$^2$ and 0.379 W/cm$^2$ respectively. The minimum power densities for the same R:C ratios have 0.333W/cm$^2$ and 0.294 W/cm$^2$ respectively. For the rib to channel width ratio of 2:2 has shown maximum power density of 0.422 W/cm$^2$ and power density of 0.300 W/cm$^2$.The optimization was performed for "Larger the Better" type of Taguchi method since 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.

**Table 3. Factors, levels, power density and S/N ratio for 16 runs of optimization**

| Run | R:C | Pressure | Temperature | Stoi.Ratio | Power Density (W/cm$^2$) | S/N Ratio |
|---|---|---|---|---|---|---|
| 1 | 1x1 | 1 | 323 | 3 | 0.350 | -9.129 |
| 2 | | 1.5 | 333 | 3.5 | 0.419 | -7.547 |
| 3 | | 2 | 343 | 4 | 0.448 | -6.974 |
| 4 | | 2.5 | 353 | 4.5 | 0.413 | -7.676 |
| 5 | 1x2 | 1 | 333 | 4 | 0.346 | -9.230 |
| 6 | | 1.5 | 323 | 4.5 | 0.394 | -8.086 |
| 7 | | 2 | 353 | 3 | 0.333 | -9.556 |
| 8 | | 2.5 | 343 | 3.5 | 0.436 | -7.218 |
| 9 | 2x1 | 1 | 343 | 4.5 | 0.294 | -10.622 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 10 | | 1.5 | 353 | 4 | 0.313 | -10.086 |
| 11 | | 2 | 323 | 3.5 | 0.354 | -9.011 |
| 12 | | 2.5 | 333 | 3 | 0.379 | -8.426 |
| 13 | 2x2 | 1 | 353 | 3.5 | 0.300 | -10.468 |
| 14 | | 1.5 | 343 | 3 | 0.402 | -7.909 |
| 15 | | 2 | 333 | 4.5 | 0.410 | -7.736 |
| 16 | | 2.5 | 323 | 4 | 0.422 | -7.488 |
| Average S/N Ratio | | | | | | -8.573 |

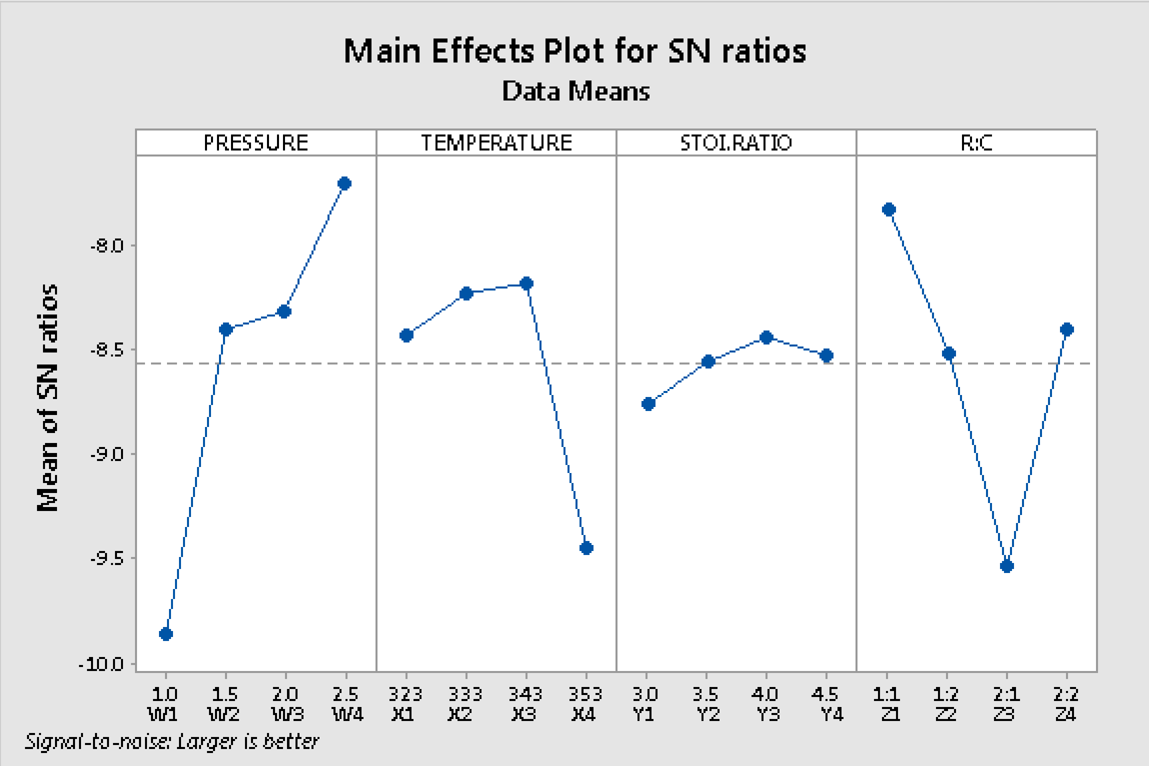


**Fig .3. Mean S/N ratio plot for R:C (W1-W4),Pressure (X1-X4),Temperature (Y1-Y4), Stoi.Ratio (Z1-Z4)**

It was concluded that the design parameter such as, rib to channel ratio of interdigitated flow channel having -1:1 as Z1, and the operating parameters like pressure - 2.5 bar as W4, temperature - 323 K as X3, Stoichiometric ratio of inlet mass flow rate - 3.5 as Y3 were the optimum parameters to show the better PEM fuel cell performance. 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. Delta value of each factor available on the MINITAB 17 software itself was shown in Table 4. The factor with highest delta value indicates higher significance factor. It was found that pressure was the predominant factor affecting the performance of PEM fuel cell. The other parameters were also influencing the performance to a considerable extent such as, rib to channel width (R:C) of interdigitated flow channel, operating temperature, stoichiometric ratio of inlet mass flow rate respectively. The percentage contribution of individual parameters, P-test and F-test on the interdigitated flow fields for the performance of PEM fuel cell has been shown in the Table 5.

It has been observed from the Table 5, operating pressure has been contributed to be 48.4 % , operating temperature was 13.1 %, the stoichiometric ratio of the reactants and R:C has contributed 5.31% and 10.9 % respectively of the PEM fuel cell performance. Also the combined effect of combination of pressure with temperature and pressure with R:C has shown 5.8 % and 5.4 % respectively contributing to peak power performance of the PEM fuel cell.

**Table 4. Mean S/N ratios, Delta and Rank for each level of factors**

| Factors | Level 1 | Level 2 | Level 3 | Level 4 | Delta | Rank |
|---|---|---|---|---|---|---|
| Rib to Channel width (R:C) | -7.832 | -8.523 | -9.536 | -8.4 | 1.705 | 2 |
| Pressure (bar) | -9.862 | -8.407 | -8.319 | -7.702 | 2.16 | 1 |
| Temperature (K) | -8.428 | -8.235 | -8.181 | -9.447 | 1.266 | 3 |
| Stoi.Ratio | -8.755 | -8.561 | -8.445 | -8.53 | 0.31 | 4 |

**Table 5.The percentage contribution of individual parameters of interdigitated flow channel**

| Factors | DOF | Sum of squares | Variance | F-test | P-Test | Contribution (%) |
|---|---|---|---|---|---|---|
| Pressure | 2 | 0.01626 | 0.00813 | 17.3 | 0.442 | 48.4 |
| Temperature | 2 | 0.00577 | 0.002885 | 6.14 | 0.485 | 13.1 |
| Stoichiometric ratio | 2 | 0.000302 | 0.000151 | 0.32 | 1.553 | 5.31 |
| R:C | 3 | 0.007674 | 0.002558 | 5.4 | 0.28 | 10.9 |
| Pressure & Temperature | 1 | 0.000074 | 0.000074 | 0.22 | 0.805 | 5.8 |
| Pressure & R:C | 3 | 0.000395 | 0.000131667 | 0.81 | 0.928 | 5.4 |
| Error | 2 | 0.00188 | 0.00094 | | | 11.1 |
| Total | 15 | 0.036774 | 0.01487 | 30.19 | 4.493 | 100 |

## Conclusion

The combined effect of all the parameters exhibited a different response compared to their individual effects. The maximum power density of optimizing the four different parameters on interdigitated flow channel of 16 $cm^2$ active area of PEM fuel cell using Minitab 17 provides 0.448 $W/cm^2$from R:C-1:1 with 2 bar operating pressure, 343 K temperature and 4 stoichiometric ratio of inlet reactant gases and $R^2$ value was arrived 95 %. The effect of operating and design parameters was affecting the performance of PEM fuel cell considerably.

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