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# Optimization of Flow Channel Design and Operating Parameters on Proton Exchange Membrane Fuel Cell Using MATLAB

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RESEARCH ARTICLE

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***Abstract***

*Operating parameters like pressure, temperature, the stoichiometric ratio of reactants, relative humidity and design parameters like rib width to channel width (L:C), the shape of the flow channel and the number of passes on the flow channel are influencing the performance of the Proton Exchange Membrane Fuel Cell (PEMFC). In this paper, optimization of operating and design parameters such as pressure, temperature, inlet reactant mass flow rate and various rib width to channel width (L:C) 1:1, 1:2, 2:1 and 2:2 on serpentine and interdigitated flow channel of 25cm$^2$ active area of the PEMFC was considered. Creo Parametric 1.0 and CFD Fluent 14.0 software packages were used to create the 3 Dimensional (3- D) model and simulation of PEMFC. The optimization was carried out on the various parameters with MINITAB 17 software and MATLAB software. From the first stage, the Landing to channel width (L:C) - 1:1 of serpentine and the interdigitated flow channel has the maximum influence on fuel cell performance and square of response factor ($R^2$) was achieved from the Taguchi method by MINITAB 17 software as 99.48 and 99.71 % respectively. In the second stage, the regression equation or mathematical model obtained from MINITAB 17 software were fed into the MATLAB software to get optimized parameters. Further the power densities were obtained corresponding to the optimized parameters using the CFD Fluent 14.0 software.*

***Keywords***

*Optimization, Taguchi method, operating parameters, design parameters, MATLAB*

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## 1 Introduction

The PEMFCs are being developed for commercial applications in the areas of transportation, back-up power and portable power. One of the main advantages is the negligible emission of pollutants, like SOx, NOx, particulates and greenhouse gases [1]. It is Eco-friendly power source which is suitable for powering both portable devices and mobile application due to their high energy density and lower operating temperature range [2]. In this paper the performance enhancement of fuel cell by optimizing the influence of various operating and design parameters using CFD Fluent 14.0 and MATLAB software packages. The PEMFC consists of polymer solid electrolyte membrane placed between an anode and a cathode. The electrochemical reaction produces electric current along with water and heat as byproducts. To attain high current, peak power density, proper temperature distribution and optimum water management the various flow channel design was used. S. Simple [3] addressed in his study that the performance of PEMFC has been influenced by the flow channel path length and the flow field design with 1.2,2 stoichiometric ratios, inlet temperatures were 70°C and 80°C, operating pressure was 1.01bar in the anode and the cathode respectively. Dyi-Huey Chang et al. [4] studied the effect of flow channel depth and flow rates on performance of PEMFC and concluded that the optimum flow rate was essential to maintain sufficient pressure, which force the reactant into channel to get proper water balance. Wei-Mon Yan et al [5] studied the impact of flow channel designs on the performance of PEMFC and concluded that the interdigitated flow field having 1.4 times better power output than the conventional flow field design. Nicholas S. Siefert [1] concluded his study that the serpentine channels are very effective to get rid of the liquid because of its high gas velocity. Atul Kumar et al. [6] Optimized the flow channel dimensions and shape in the flow field of a single pass serpentine flow field design. In his study, he concluded that the different shape of cross section leads to the excess hydrogen consumption in the anode, thus it can influence the performance of the PEMFC. However, water accumulation leads the fuel cell performance unpredictable and unreliable under the nominally identical operating conditions. So the essential issue for

PEMFCs can be resolved through appropriate design of flow channels for effective removal of water built on the flow field (bipolar) plates. Nattawut Jaruwasupant and Owejan J.P [7, 8] have investigated that to enhance the performance of PEMFC and reliability, it is important to know more about the mechanism that causes a performance loss, like current density distributions, non-uniform concentration, high ionic resistance result of dry membrane and high diffusive resistance because of the flooding on the cathode. Xianguo Li and Chi-Young Jung [9, 10] has addressed in their study that Hydration of membrane in the PEMFC is used to keep up the performance. If it is not maintained properly, flooding and dehydration would occur which will affect the fuel cell performance. So identifying the proper channel and flow field design are also affecting the performance of fuel cell considerably [11]. Zeroual et al. [12] concluded that the operating parameters like temperature, pressure and reactants influenced the performance of PEMFC considerably. The increasing of inlet pressure, improved the consumption of reactants and more uniform distribution. The impact of channel design also varied the consumption of reactants and consequently increases water production. Atilla Biyikoglu [13] concluded that the equal current distribution must be ensured through uniform velocity distribution of the reactants at the flow channel. Otherwise, parasitic current may be occurring due to potential differences. The cell temperature must be kept uniformly so that the heat produced by electrical resistance and electrochemical reactions can be removed from the cell. It is clearly evident that there is a need for immediate attention towards analyzing and optimizing the simultaneous influence of operating and design parameters for the performance of the PEMFC using CFD Fluent 14.0 and MATLAB software packages. In this work focusing on implementation of Taguchi method for optimizing the design and operating parameters. P. Karthikeyan et al. [14] was optimized a single channeled fuel cell of 125 mm flow channel length with ten operating and design parameters using Taguchi method. Horng-Wen Wu et al. [15] studied the effect of operating parameters such as flow orientation, temperature of a fuel cell, anode and cathode humidification temperatures, anode and cathode stoichiometric flow ratios by Taguchi method on performance enhancement of PEMFC. Also, he studied the effect of serpentine flow channel with the best arrangement of cuboid rows with the minimum pressure drops in anode and cathode channels and maximum electrical power on PEMFC performance [16]. Numerous parameters such as fuel cell operating temperatures, cathode and anode humidification temperatures, operating pressures, and reactant flow rate on affecting the PEMFC performance by using the Taguchi method and the relevant response factors were used to set the training patters of the neural network by Sheng-Ju Wu et al. [17]. Wei-Lung Yu et al. analyzed the performance of a fuel cell with various operating parameters in two stages. In the first stage, DOE was used to find the fractional factorial design and the next stages was to find out the operating parameters by using Taguchi method [18]. Based on this study, the interactions between operating temperature and pressure have a significant effect on the fuel cell performance. Among them, the operating pressure is the most important significant parameter on the effect of fuel cell performance. When the operating pressure increases, it should simultaneously lower the effects of other factors. Thus, this paper has a detailed study about the optimization of various pressure ranges 1 ,1.5, 2 and 2.5 bar temperature of 323K, 333K, 343K and 353K, anode and cathode inlet reactant mass flow rates of 3 , 3.5, 4 and 4.5 times to the theoretical value and various rib to channel width (L:C)- 1:1, 1:2, 2:1 & 2:2 on serpentine and interdigitated flow channel of 25 $cm^2$ active area of PEMFC and their influence in the performance were compared. Numerical modelling was chosen as a platform for analysis because to study the combined effect of all such factors and also which are not easy to change for each trial, while running experiments.

## 2 Model Development

Before importing the model to CFD Fluent 14.0 creating a good mesh by ANSYS 14 ICEM software was one of the most difficult steps involved in modeling. It needs a careful balance of creating enough computational cells to capture the geometry without creating much. Care ought to be taken such that it should not exceed the available memory of the meshing computer. Many other factors must also be considered into account in order to generate a computational mesh that provides results when simulated [19].

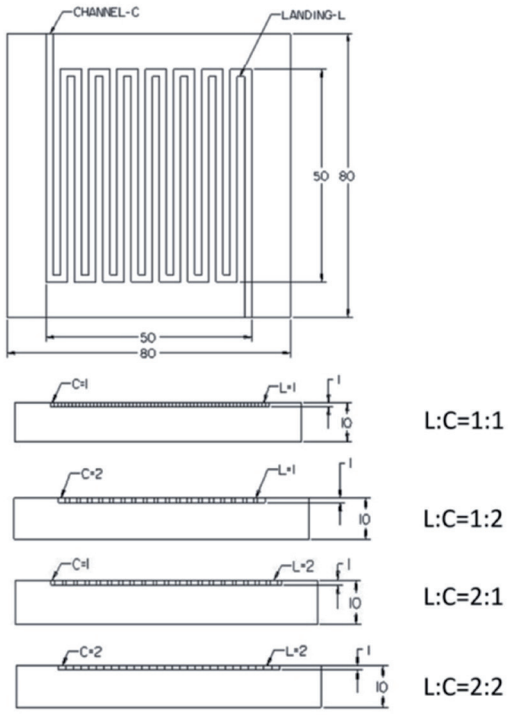



**Fig. 1** Various rib to channel width (L: C) (a) 1:1 (b)1:2 (c) 2:1 and (d) 2:2 of serpentine flow channel of 25 $cm^2$ active area.

Three dimensional (3-D) PEMFC model for 25cm$^2$ acting area of serpentine and interdigitated flow channel with various landings to channel width configurations were created by Creo Parametric 1.0 as shown in Fig. 1 and 2. The modeling was done by creating individual parts of the PEMFC and the dimensions of parts such as the anode and cathode flow channel, the anode and cathode catalyst layers, solid polymer electrolyte membrane and GDL as shown in the Table 1. The various geometrical models (L: C-1:1, 1:2, 2:1 and 2:2) of serpentine and the interdigitated flow channel were meshed by using ICEM 14.0 (a module of Ansys 14.0). The assignments of zones for various parts were done by Workbench 14.0.

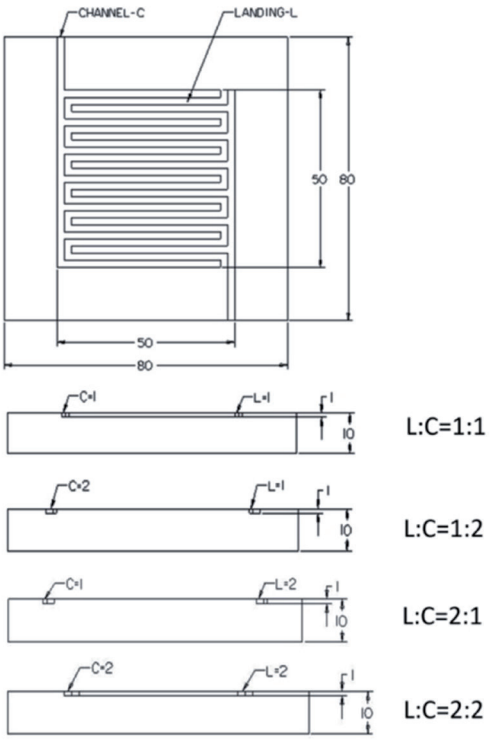



**Fig. 2** Various rib to channel width (L: C) (a)1:1 (b)1:2 (c)2:1 and (d)2:2 of interdigitated flow channel of 25 cm$^2$ active area.

## 2.1 Meshing On PEMFC

After geometry building, the next step was discretization done by ANSYS 14 ICEM software. The meshing method was used as Cartesian grid that helps within the formation of hexahedral mesh to get accurate results. Hence the entire cell was divided into a finite range of discrete volume elements or computational cells to solve the equations associated with the fuel cell simulation. Blocking was done by a split block method and meshing was done by a Cartesian method with a body fitted mesh. The projection factor determines how closely the edges of the mesh match up with the grid and it was set to 1. In our studies, minimum of 527481 and maximum of 566313 nodes, minimum 717128 and maximum 739808 elements was considered.

## 2.2 Equations

The simulation was solved by simultaneous equations like conservation of mass,momentum,energy,species concentration, Joule heating reaction, Butler–Volmer equation and the Nernst equation to obtain reaction kinetics of the PEMFC. The model used to consider the system as 3-D, steady state, and inlet gases as ideal condition, system as an isothermal and laminar flow, incompressible fluid, thermo physical properties as constant and the porous GDL, two catalyst layers and the membrane as an isotropic.

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\partial v) = 0 \tag{1}$$

Conservation of Momentum

$$\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\partial v v) = -\nabla \rho + \nabla \cdot \left(\mu^{eff} \nabla v\right) + S_m \tag{2}$$

Conservation of Energy

$$\begin{aligned} &\left(\rho C_p\right)_{eff} \frac{\partial T}{\partial t} + \left(\rho C_p\right)_{eff} (v \cdot \nabla T) = \nabla \left(k_{eff} \nabla T\right) + S_e \\ &\left(\rho C_p\right)_{eff} = (1-\varepsilon)\rho_s C_{p,s} + \varepsilon \rho C_p \\ &k_{eff} = -2k_s + \left[\frac{\varepsilon}{2k_s + k} + \frac{1-\varepsilon}{3k_s}\right] \end{aligned} \tag{3}$$

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

| S No | Part name | Width (mm) | Length (mm) | Thickness (mm) | Zone Type |
|---|---|---|---|---|---|
| 1 | Anode and Cathode Flow Channel | 80 | 80 | 10 | Fluid |
| 2 | Anode and Cathode Catalyst | 50 | 50 | 0.08 | Fluid |
| 3 | Membrane | 50 | 50 | 0.127 | Fluid |
| 4 | GDL Anode and Cathode | 50 | 50 | 0.3 | Fluid |

Condensation or evaporation of water vapor/liquid water is leading to heat generation or heat absorption in the Catalyst layer

$$S_e = |j|\left[|\Delta V_{act}| - \frac{T\Delta S}{nF}\right] + \left(\frac{i_e^2}{k_s^{eff}} + \frac{i_m^2}{k_m^{eff}}\right) - \sigma A_{fg}\left(x_{sat-}x_{\mathrm{H_2O(g)}}\right)\Delta h_{fg} \tag{4}$$

Current flow though the solid parts of the GDL

$$S_e = \frac{i_e^2}{k_s^{eff}} - \sigma A_{fg}\left(x_{sat-}x_{\mathrm{H_2O(g)}}\right)\Delta h_{fg} \tag{5}$$

Ohmic losses in Membrane (Transport of ions)

$$S_e = \frac{i_m^2}{k_m} \tag{6}$$

Darcy Law through the Porous Media

$$S_m = -\frac{\mu}{K}\varepsilon v \tag{7}$$

Conservation of Species

$$\frac{\partial\left(\varepsilon p x_i\right)}{\partial t} + \nabla\left(v\varepsilon\rho_i\right) = \nabla\cdot\left(\rho D_i^{eff}\nabla x_i\right) + S_{s,i} \tag{8}$$

$S_{s,H_2} = -j_a\frac{M_{H_2}}{2F}$ - Rate of hydrogen consumption in the anode catalyst layer

$S_{s,O_2} = -j_C\frac{M_{O_2}}{2F}$ -Rate of hydrogen consumption in the cathode catalyst layer

$S_{s,H_2O(1)} = j_C\frac{M_{H_2O}}{2F} - \sigma A_{fg}\left(x_{sat} - x_{H_2O(g)}\right)$- Rate of liquid vapor formation

$S_{s,H_2O(g)} = \sigma A_{fg}\left(x_{sat} - x_{H_2O(g)}\right)$ - Rate of water vapor formation

Stefan-Maxwell equation for multi-component species – Mole fraction of the components

$$\frac{dx_i}{dz} = RT\sum\frac{x_iN_j - x_jN_i}{PD_{ij}} \tag{9}$$

Conservation of Charge

$\nabla\cdot\left(k_s^{eff}\nabla\phi_s\right) = S_{\phi s}$ - Electric current

$\nabla\cdot\left(k_m^{eff}\nabla\phi_m\right) = S_{\phi m}$ - Ionic current

$S_{\phi s} = -j_a$ and $S_{\phi m} = j_{ci}$ - At the anode catalyst layer

$S_{\phi s} = j_c$ and $S_{\phi m} = -j_{ci}$ - At the cathode catalyst layer (10)

Electrochemical equation

$$V_{cell} = V_{rev} - \frac{RT}{\alpha F}\ln\left(\frac{i}{i_o}\right) - i\left(r_{ele} - r_{ion}\right) - \frac{RT}{nF}\ln\left(1 - \frac{i}{i_{\lim}}\right) \tag{11}$$

Nernst equation for reversible for cell potential

$$v_{rev} = v_{rev}^o + \frac{RT}{nF}\ln\left(\frac{P_{\mathrm{H_2}}P_{\mathrm{O_2}}^{0.5}}{P_{\mathrm{H_2O}}}\right) \tag{12}$$

Butler-Volmer equation for activation over potential

$$\Delta V_{act} = \frac{RT}{nF}\ln\left(\frac{i}{i_o}\right)$$
$$i_o = i_o^{ref}a_cL_c\left(\frac{P_r}{P_r^{ref}}\right)^{\gamma}\exp\left[\frac{-E_c}{RT}\left(1 - \frac{T}{T_{ref}}\right)\right] \tag{13}$$

Concentration over potential

$$\Delta V_{conc} = \frac{RT}{nF}\ln\left(1 - \frac{i}{i_{\lim}}\right)$$
$$i_{\lim} = \frac{nFDC_B}{\delta} \tag{14}$$

Empirical equation for the membrane conductivity as a function of membrane water content and the temperature

$$\sigma = \left(0.005139\lambda - 0.00326\right)\exp\left[1268\left(\frac{1}{303} - \frac{1}{T}\right)\right]$$
$$\lambda = 0.043 + 17.8a - 39.85a^2 + 36a^3 \qquad 0 < a \le 1$$
$$\lambda = 14 + 1.4\left(a - 1\right) \qquad 0 < a \le 3 \tag{15}$$
$$a = \frac{X_{H_2O}P}{P_{sat}}$$

Water Transport Mechanism of Membrane

a) Diffusion due to concentration difference:

$$N_{H_2O,diff} = D_w\frac{\Delta C}{\Delta Z}$$
$$D_w = D_\lambda\exp\left(2416\left(\frac{1}{303} - \frac{1}{T_c}\right)\right)$$
$$D_\lambda = \begin{pmatrix} 10^{-6}, \lambda < 2 \\ 10^{-6}\left(1 + 2\left(\lambda + 2\right), 2 \le \lambda \le 3\right) \\ 10^{-6}\left(3 - 1.67\left(\lambda - 3\right), 3 < \lambda < 4.5\right) \\ 1.25\cdot 10^{-6}, \lambda \ge 4.5 \end{pmatrix} \tag{16}$$

b) Electro-osmotic drag:

$$N_{H_2O,drag} = n_d\frac{1}{F}$$
$$n_d = 0.0029\lambda^2 + 0.05\lambda - 3.4\cdot 10^{-19} \tag{17}$$

c) Pressure difference:

$$N_{H_2O,\mathfrak{p}_r} = K_p\frac{\Delta P}{\Delta Z} \tag{18}$$

The final steps involved were the adoption of boundary condition with physical and operating parameters of PEMFC for solving the above mentioned reaction kinetics. The boundary conditions for the inlet gases at anode and cathode were set as "mass flow-inlet" whereas for the outlet of the anode and cathode was given the boundary conditions as "pressure-outlet". The anode was grounded (V = 0) and the cathode terminal was set at a fixed potential that was less than the open-circuit potential and gradually increasing by 0.1Volt. Both the terminals should be assigned the boundary type as „WALL".

Voltage jump zones can optionally be placed between the various components (such as between the gas diffusion layer and the current collector) and the effect of gravity was neglected.

### 2.3 Solver

A control volume approach based on commercial solver FLUENT 14.0 was used to solve the various governing equations. The 3D, 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 and viscous resistance at anode and cathode side was 0.5 and 1E12 ($1/m^2$). Open circuit voltage was set at 0.95V in the anode side and 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 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 specification of the PEMFC was listed in Table 2.

### 2.4 Adaptation of Taguchi Method

Taguchi method can be used to find out the most optimum combination among the input parameters (Operating and Design) which will result in getting the maximum possible output which cause in the performance enhancement of PEMFC. Two stages of analysis were performed as coarse optimization of factors and refinement of coarsely optimized factors. 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 during 16 runs itself. The factors considered for the first stage of analysis, L: C, pressure, temperature, anode and cathode inlet mass flow rate. The inlet mass flow rate of the reactants as 3, 3.5, 4 and 4.5 means that number of times the theoretical mass flow rate to be multiplied. The theoretical value of hydrogen in the anode side was 4.33E-07 kg/sec and cathode side was 3.33E-06 kg/sec.

**Table 2** The specification of the PEMFC

| S No | Properties | Values |
|---|---|---|
| 1 | Anode reference current density($A/cm^2$) | 10000 |
| 2 | Cathode reference current density($A/cm^2$) | 20 |
| 3 | Anode reference concentration($kmol/m^3$) | 1 |
| 4 | Cathode reference concentration($kmol/m^3$) | 1 |
| 5 | Anode exchange co efficient | 2 |
| 6 | Cathode exchange co efficient | 2 |
| 7 | Reference Diffusivity of $H_2$ ($m^2/s$) | 3E-5 |
| 8 | Reference Diffusivity of $O_2$ ($m^2/s$) | 3E-5 |
| 9 | Reference Diffusivity of $H_2O$($m^2/s$) | 3E-5 |

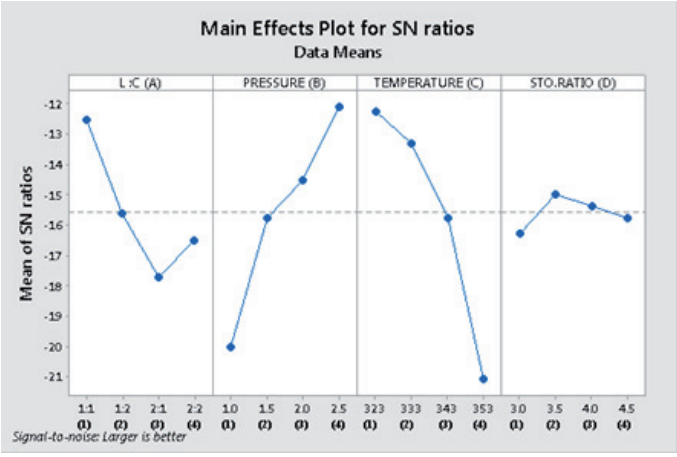
## 3 Results and Discussion

### 3.1 Optimization of design and operating parameters of first stage

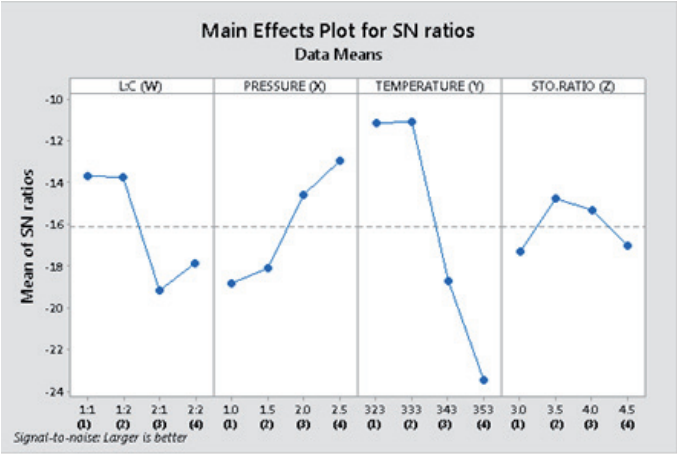
As per L16 orthogonal array, the inputs were given to the analysis software and having all other parameters constant. The power density from polarization curve was found by a numerical study using CFD Fluent 14.0 software package for all 16 runs and the corresponding Signal/Noise (S/N) ratios were found from MINITAB 17 software and were shown in Table 3. The S/N ratio, which was the ratio of controlled and uncontrolled factors calculated using the formula -10 log10 ($1/P^2$) where P is the power density.

The optimization was performed for "Larger the Better" type of Taguchi method for power output of PEMFC 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.

It was concluded that the design parameter, landing to channel ratio of serpentine and interdigitated flow channel having 1:1 at A1, and the operating parameters like pressure 2.5 bar as B4, temperature 323 K as C1, theoretical consumption of mass flow rate 3.5 as D2 were the optimum parameters to show the better performance of PEMFC.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 Delta value of each factor available on the MINITAB 17 software itself was shown in Table 4. The factor in highest delta value indicates higher significance. It was found that the temperature was the predominant factor affecting the performance of fuel cell. The other parameters were also influencing the output of PEMFC to a considerable extent, pressure, rib to channel width (L: C) of serpentine and interdigitated flow channel and Stoichiometric ratio respectively.




(a)




(b)

**Fig. 3** Mean S/N ratio plot for L: C (A&W), Pressure (B&X), Temperature (C&Y), Stoichiometric ratio (D&Z) of (a) Serpentine and (b) Interdigitated flow channel

**Table 3** Factors, levels, power density and S/N ratio of serpentine and interdigitated flow channel for 16 runs of coarse optimization.

| Run | (L:C) | Pressure (bar) | Temperature (K) | Stoichiometric ratio | Serpentine | | Interdigitated | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Power density ($W/cm^2$) | S/N Ratio | Power density ($W/cm^2$) | S/N Ratio |
| 1 | 1:1 | 1 | 323 | 3 | 0.224 | -12.98 | 0.279 | -12.66 |
| 2 | | 1.5 | 333 | 3.5 | 0.278 | -11.11 | 0.286 | -12.24 |
| 3 | | 2 | 343 | 4 | 0.259 | -11.75 | 0.219 | -13.18 |
| 4 | | 2.5 | 353 | 4.5 | 0.194 | -14.24 | 0.105 | -15.91 |
| 5 | 1:2 | 1 | 333 | 4 | 0.141 | -17.04 | 0.269 | -18.78 |
| 6 | | 1.5 | 323 | 4.5 | 0.224 | -12.99 | 0.285 | -12.43 |
| 7 | | 2 | 353 | 3 | 0.079 | -22.04 | 0.076 | -17.37 |
| 8 | | 2.5 | 343 | 3.5 | 0.304 | -10.35 | 0.306 | -11.49 |
| 9 | 2:1 | 1 | 343 | 4.5 | 0.064 | -23.82 | 0.045 | -18.59 |
| 10 | | 1.5 | 353 | 4 | 0.081 | -21.8 | 0.049 | -17.67 |
| 11 | | 2 | 323 | 3.5 | 0.244 | -12.25 | 0.250 | -11.02 |
| 12 | | 2.5 | 333 | 3 | 0.2245 | -12.98 | 0.268 | -10.47 |
| 13 | 2:2 | 1 | 353 | 3.5 | 0.0491 | -26.18 | 0.052 | -18.07 |
| 14 | | 1.5 | 343 | 3 | 0.1407 | -17.04 | 0.060 | -17.19 |
| 15 | | 2 | 333 | 4.5 | 0.251 | -12.01 | 0.292 | -10.60 |
| 16 | | 2.5 | 323 | 4 | 0.289 | -10.77 | 0.294 | -10.88 |
| Overall mean of S/N ration (η) | | | | | | -15.59 | | -16.11 |

**Table 4** Mean S/N ratios, Delta and Rank for each level factor of (A) Serpentine and (B) Interdigitated flow channel

| Factors | Level 1 | | Level 2 | | Level 3 | | Level 4 | | Delta | | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | A | B | A | B | A | B | A | B | |
| Rib to Channel width (L:C) | -12.52 | -13.67 | -15.6 | -13.75 | -17.72 | -19.15 | -16.5 | -17.87 | 5.2 | 5.48 | 3 |
| Pressure (bar) | -20.01 | -18.81 | -15.75 | -18.08 | -14.51 | -14.57 | -12.08 | -12.98 | 7.92 | 5.83 | 2 |
| Temperature (K) | -12.25 | -11.16 | -13.28 | -11.1 | -15.74 | -18.73 | -21.08 | -23.45 | 8.83 | 12.35 | 1 |
| Stoichiometric ratio | -16.26 | -17.33 | -14.97 | -14.74 | -15.35 | -15.34 | -15.77 | -17.04 | 1.28 | 2.59 | 4 |

### 3.2 Optimization of design and operating parameters

But in this analysis, all the factors were considered irrespective of their significance for better performance on PEMFC. The level with a higher S/N ratio was considered to be optimum level and optimum combination of operating and design parameters was founded for serpentine and interdigitated flow channel on Fig. 3 to be A1B4C1D2 and W1X4Y2Z2 respectively. The maximum power of this combination founded using Taguchi calculation was 0.55853 W/cm² and 0.61962 W/cm² respectively as shown by Eq. (19) and (20). S/N ratio for optimum combination

$$\begin{aligned}\eta_{opt} &= \eta + \Delta A1 + \Delta B4 + \Delta C1 + \Delta D2 + = -10\log 10\left(1/P_{max}{}^2\right)\\ \eta_{opt} &= -15.587 + \left(3.067 + 3.507 + 3.337 + 0.617\right)\\ &= -5.05912 = -10\log 10\left(1/P_{max}{}^2\right)\\ P_{max} &= 0.55853\,W/cm^2\end{aligned} \tag{19}$$

S/N ratio for optimum combination

$$\begin{aligned}\eta_{opt} &= \eta + \Delta W1 + \Delta X4 + \Delta Y2 + \Delta Z2 + = -10\log 10\left(1/P_{max}{}^2\right)\\ \eta_{opt} &= -16.111 + \left(2.441 + 3.131 + 5.011 + 1.371\right)\\ &= -4.15712 = -10\log 10\left(1/P_{max}{}^2\right)\\ P_{max} &= 0.61962\,W/cm^2\end{aligned} \tag{20}$$

(ΔA1 Corresponds to difference of overall S/N ratio mean and maximum value of S/N ratio mean for all the four levels corresponding to the factor A (15.587-12.52=3.067) and ΔB4 Corresponds to difference of overall S/N ratio mean and maximum value of S/N ratio mean for all the four levels corresponding to the factor B (15.587-12.08=3.507) in Table 4 so on, η corresponds to the overall mean of the S/N ratio in Table 3).

### 3.3 Optimized parameters using MATLAB

The second stage, regression equation or mathematical model obtained from MINITAB 17 software was fed into the MATLAB software to get optimized parameters of serpentine and interdigitated flow channel having 25 cm² active areas. In order to validate the power density obtained from the MATLAB, the optimum combination of parameters was given as input to CFD Fluent 14.0 software package. The maximu peak power density was found to be 0.2785276 W/cm² in serpentine flow channel of 25cm² active area with landing to channel width (L:C)1:1 for cell potential of 0.4 V and the current density 0.696319 A/cm².In interdigitated flow channel of 25cm² active area with landing to channel width (L:C) 1:2 the maximum peak power density was found to be 0.29736765 W/cm² and the current density 0.660817 A/cm² at cell potential of 0.45 V.

The power density for serpentine and interdigitated flow channel with 25 cm² active area of various landing to channel width (L: C) has been achieved for various combinations of optimized parameters was shown in the Table 5. The maximum power density corresponding to Taguchi calculations was in good agreement with analysis software results indicating the compatibility of Taguchi method for PEMFC applications [17].

## 4 Conclusions

The combined effect of all the parameters exhibited a different response compared to their individual effects. Optimizing the four different parameters using Minitab 17 the $R^2$ value was obtained from serpentine and interdigitated flow channel of 25cm² active area of PEMFC with various landings to channel width (L:C) as 99.48% and 99.71% respectively. The peak power density achieved by CFD Fluent 14.0 software by using regression equation obtained from MATLAB was found to be 0.2785276 W/cm² in serpentine flow channel of 25cm² active area of PEMFC with landing to channel width (L:C)1:1 for cell potential of 0.4 V and the current density 0.696319 A/cm².

**Table 5** Optimum power density for various combinations of parameters

| Flow channel | L:C | Pressure (bar) | Temperature (K) | Stoichiometric Ratio | Power density (W/cm²) |
|---|---|---|---|---|---|
| Serpentine | 1:1 | 2.49 | 329.9 | 3.98 | 0.27853 |
| | 1:2 | 2.49 | 327.3 | 3.97 | 0.27457 |
| | 2:1 | 2.49 | 329.7 | 3.96 | 0.24781 |
| | 2:2 | 2.50 | 328.0 | 3.96 | 0.27258 |
| Interdigitated | 1:1 | 2.49 | 323.8 | 4.24 | 0.28955 |
| | 1:2 | 1.00 | 323.0 | 4.24 | 0.29737 |
| | 2:1 | 1.00 | 323.0 | 4.23 | 0.25483 |
| | 2:2 | 1.41 | 323.0 | 4.24 | 0.29237 |

In interdigitated flow channel of 25cm² active area of PEMFC with landing to channel width (L:C)1:2, the maximum peak power density was found to be 0.29736765 W/cm² and the current density 0.660817 A/cm² at cell potential of 0.45 V. The effect of operating and design parameters was affecting the performance of PEMFC more significantly.

## References


[1] Siefert, N. S., Litster, S. "Voltage loss and fluctuation in proton exchange membrane fuel cells: The role of cathode channel plurality and air stoichiometric ratio." *Journal of Power Sources*. 196(4), pp. 1948-1954. 2011. DOI: 10.1016/j. jpowsour. 2010.10.026

[2] Manso, A. P., Garikano, X., Mujika, G. M., Marzob, F.F., Barranco, J. "Influence of geometric parameters of the flow fields on the performance of a PEM fuel cell. A review." *International Journal of Hydrogen Energy*. 37, pp. 15256-15287. 2012. DOI: 10.1016/j.ijhydene. 2012.07.076

[3] Shimpalee, S., Greenway, S., Van Zee, J. W. "The impact of channel path length on PEMFC flow-field design." *Journal of Power Sources*. 160, pp. 398-406. 2006. DOI:10.1016/j.jpowsour.2006.01.099

[4] Chang, D-H., Hung, J-C. "Effects of Channel Depths and Anode Flow Rates on the Performance of Miniature Proton Exchange Membrane Fuel Cells." *International Journal of Applied Science and Engineering*. 10(4), pp. 273-280. 2012.

[5] Yan, W-M., Chen, C-Y., Mei, S-C., Soong, C-Y., Chen, F. "Effects of operating conditions on cell performance of PEM fuel cells with conventional or interdigitated flow field." *Journal of Power Sources*. 162, pp. 1157-1164. 2006. DOI:10.1016/j.jpowsour.2006.07.044

[6] Kumar, A., Reddy, R. G. "Effect of flow channel dimensions and shape in the flow field distributor on the performance of polymer electrolyte membrane fuel cells." *Journal of Power Sources*. 113, pp. 11-18. 2003. DOI: 10.1016/S0378-7753(02)00475-5

[7] Jaruwasupant, N., Khunatorn, Y. "Effects of difference flow channel designs on Proton Exchange Membrane Fuel Cell using 3-D Model." *Energy Procedia*. 9, pp. 326-337. 2011. DOI: 10.1016/j.egypro.2011.09.035

[8] Owejan, J. P., Trabold, T. A., Jacobson, D. L., Arif, M., Kandlikar, S. G. "Effects of flow field and diffusion layer properties on water accumulation in a PEM fuel cell." *International Journal of Hydrogen Energy*. 32, pp. 4489-4502. 2007. DOI: 10.1016/j.ijhydene.2007.05.044

[9] Li, X., Sabir, I., Park, J. "A flow channel design procedure for PEM fuel cells with effective water removal." *Journal of Power Sources*. 163, pp. 933-942. 2007. DOI: 10.1016/j.jpowsour.2006.10.015

[10] Jung, C-Y., Lee, C-S., Yi, S-C. "Computational analysis of transport phenomena in proton exchange membrane for polymer electrolyte fuel cells." *Journal of Membrane Science*. 309, pp. 1-6. 2008. DOI: 10.1016/j.memsci.2007.10.017

[11] Higier, A., Liu, H. "Effects of the difference in electrical resistance under the land and channel in a PEM fuel cell." *International Journal of Hydrogen Energy*. 36, pp. 1664-1670. 2011. DOI: 10.1016/j.ijhydene.2010.11.007

[12] Zeroual, M., Bouzida, B. S., Benmoussa, H., Bouguettaia, H. "Numerical study of the effect of the inlet pressure and the height of gas channel on the distribution and consumption of reagents in a fuel cell (PEMFC)." *Energy procedia*. 18, pp. 205-214. 2012. DOI: 10.1016/j.egypro.2012.05.032

[13] Bıyıkoglu, A. "Review of proton exchange membrane fuel cell models." *International Journal of Hydrogen Energy*. 30, pp. 1181–1212. 2005. DOI: 10.1016/j.ijhydene.2005.05.010

[14] Karthikeyana, P., Muthukumar, M., Shanmugam, V. S., Kumar, P. P., Murali, S., Kumar, S. A. P. "Optimization of Operating and Design Parameters on Proton Exchange Membrane Fuel Cell by using Taguchi method." *ProcediaEngineering*. 64, pp. 409-418. 2013. DOI: 10.1016/j.proeng.2013.09.114

[15] Wu, H-W., Gu, H-W. "Analysis of operating parameters considering flow orientation for the performance of a proton exchange membrane fuel cell using the Taguchi method." *Journal of Power Sources*. 195, pp. 3621-3630. 2010. DOI: 10.1016/j.jpowsour.2009.11.128

[16] Wu, H-W., Ku, H-W. "Effects of modified flow field on optimal parameters estimation and cell performance of a PEM fuel cell with the Taguchi method." *International journal of hydrogen energy*. 37, pp. 1613-1627. 2012. DOI: 10.1016/j.ijhydene.2011.09.115

[17] Wu, S-J., Shiah, S-W., Yu, W-L. "Parametric analysis of proton exchange membrane fuel cell performance by using the Taguchi method and a neural network." *Renewable Energy*. 34, pp. 135-144. 2009 DOI: 10.1016/j.renene.2008.03.006

[18] Yu, W-L., Wu, S-J., Shiah, S-W. "Parametric analysis of the proton exchange membrane fuel cell performance using design of experiments." *International Journal of Hydrogen Energy*. 33, pp. 2311-2322. 2008. DOI: 10.1016/j.ijhydene.2008.02.040

[19] Iranzo, A., Munoz, M., Rosa, F., Pino, J. "Numerical model for the performance prediction of a PEM fuel cell. Model results and experimental validation." *International Journal of Hydrogen Energy*. 35, pp. 11533-11550. 2010. DOI: 10.1016/j.ijhydene.2010.04.129