PERFORMANCE ENHANCEMENT OF 64 cm^2 ACTIVE AREA OF PEM FC BY USING TAGUCHI METHOD

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ABSTRACT

The Proton Exchange Membrane Fuel Cell (PEMFC) is an electrochemical device and its performance depends on the design and operating parameters. In this paper, optimization of operating and design parameters on serpentine flow field of 64 cm^2 effective area of the PEM fuel cell was considered. The design was done by Creo Parametric 2.0 software and analyses and optimization by Taguchi method was done by CFD Fluent 14.5 and Minitab 17 software respectively. Based on the optimization study, the landing to channel width ratio (L: C) - 1:1 has given 0.163 W/cm^2 power density also it has maximum influence on PEM fuel cell performance and square of response factor (R^2) was achieved by Taguchi method as 99.67 %.

Keyword: - *Serpentine flow field; Taguchi method; Optimization; Design and operating parameters; CFD.*

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1. INTRODUCTION

Fuel cells are the electrochemical energy converting device which converts chemical energy into electrical energy without any conventional combustion process. Among many types of fuel cells Polymer Electrolyte Membrane fuel Cell (PEMFC) is produced with high power density with low operating temperature for light weight and compact with negligible pollution studied by Maher A.R [1]. The internal combustion engine can be replaced by PEMFC for transportation due to its high energy efficient, quick startup, quiet and clean. Since a PEMFC simultaneously involves electrochemical reactions, current distribution, water balance and heat transfer studied by Sukkee Um et al [2]. The water management of PEM fuel cell has become an important task, because more water accumulation causes “flooding” or less water causes dryness of membrane can adversely affect the performance and lifetime of PEM fuel cells. Sukkee Um [3] revealed in his study that the water transport in PEMFC was discussed to show various water transport regimes, such as anode side water loss, cathode side flooding and the equilibrium condition of water at the channel outlets. Hence, the effects of the flow channel, membrane thickness, and inlet gas humidity are important to enhance the performance of PEM fuel cell. 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 forces the reactant into channel to get proper water balance. Nicholas S. Siefert [5] concluded in his study that the serpentine channels are very effective to remove the liquid because of its high gas velocity. However, Water accumulation leads the fuel cell performance unpredictable and unreliable under the nominally identical operating conditions. So the critical issue for PEMFCs can be resolved through appropriate design of flow channels for effective removal of water built on the flow field (bipolar) plates. M. Zeroual et al [6] analyzed that the effects of inlet pressure and channel height on the distribution and consumption of reagents. The gas flow was assumed as incompressible, isothermal, unsteady and laminar, straight channeled flow fields were modeled in the anode and cathode sides. The simulation results showed that the increasing inlet pressure will improve consumption of oxygen and hydrogen and more homogeneous distribution. The effect of height was more important for a higher pressure inlet. It was noticed that an increased consumption of species and consequently an increase in water production if the height of the channel was smaller. Wei-Lung Yu et al [7] analyzed the two stages of optimization, in the first stage DOE was used to determine the significant effects on a response and the interactions between the six operating parameters like operating pressures, anode and cathode humidification temperatures, operating temperatures, anode and cathode stoichiometric flow ratios. In the second stage, the optimal combination of factors of a fuel cell was analyzed by Taguchi method. It was concluded that the possible way to increase the performance of PEM fuel cell by simultaneously increasing both the operating pressure and temperature and the remaining factors were at appropriate conditions. Atul Kumar, Ramana G. Reddy [8] studied the improvement on the performance of polymer electrolyte membrane fuel cell through optimization of the channel dimensions and shape in the flow-field of bipolar plates. Single-path serpentine flow-field design was used for studying the effect of channel dimensions on the hydrogen consumption at the anode. Nattawut Jaruwasupant and Yottana Khunatorn [9] studied the effects of serpentine flow channel designs on PEM fuel cell for reaction gas distributions, the relationship between channel curvature, channel length, velocity distribution and characteristics of flow field with pressure drop by using the three dimensional computational fluid dynamics (CFD) numerical model for the on the performance of Polymer Electrolyte Membrane fuel cells. Effects of curve channel length and widths of a flow field plate were studied in an effort to optimize the channel dimensions and it was concluded that a better design of the gas flow field was required to improve the gas distribution and water management. Horng-Wen Wu and Hui-Wen Gu [10] has applied the Taguchi method to find the optimal combination of six operating parameters like operating and anode, cathode humidification temperatures, flow orientation, anode, and cathode stoichiometric flow ratios of a PEM fuel cell. The results showed that the flow orientation, operating temperature and anode and cathode humidification temperatures were significant factors for affecting the performance of the fuel cell.

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 [11]. The results were concluded that, the L: C- 1:2 has maximum power density of 0.422 W/cm^2 and square of response factor (R^2) was achieved by Taguchi method as 97.90 %. Optimization of various operating and design parameters on serpentine flow channel of 25cm^2 active area of the PEMFC was studied in two stages of Taguchi method by Lakshminarayanan et al [12]. The analysis result revealed that the first stage of optimization, the L: C- 1:1 has maximum influence on PEMFC performance and square of response factor (R^2) was achieved by Taguchi method as 99.9 %. In the second stage of fine-tune optimization, the enhancement of power density from

0.372 W/cm^2 to 0.3785 W/cm^2 on PEMFC performance. Kanani et al. [13] 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 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 [14]. It is clearly indicated that immediate attention is required for optimizing the simultaneous influence of design and operating parameters for the performance investigation of the PEM fuel cell. Hence this paper has a detailed investigation 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 field of 64 cm^2 active area of PEM fuel cell are to be studied and influence their performance are compared.

2. MODEL DEVELOPMENT

2.1 Geometrical Modeling

The first was the modeling the geometry of the fuel cell as per the dimension using Creo Parametric. The modeling was done by creating individual parts of the single pass PEM fuel cell such as to include the anode and cathode GDL, solid polymer electrolyte membrane, the anode and cathode catalyst layers. The various single pass geometrical models form the basis for creating a computational mesh. The dimensions of fuel cell as mentioned below

- Anode & Cathode Flow field - 8cm x8cm x 1cm
- Anode & Cathode catalyst - 8cm x8cm x 0.008 cm
- GDL anode & cathode - 8cm x8cm x 0.0127cm
- Membrane - 8cm x8cm x 0.03 cm

The Anode & Cathode Flow field has been assigned as solid zone type remaining parts has assigned as fluid type. Three dimensional (3-D) PEM fuel cell model with serpentine flow field of various landing to channel width configurations were created by Creo Parametric 1.0 as shown in Fig.1. 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. Creating a good mesh has been one of the most difficult steps involved in modeling. It requires a careful balance of creating enough computational cells to capture the geometry without creating much of its care should be taken such that it would not exceed the available memory of the meshing computer. The third and final step was involved adoption of boundary condition with physical and operating parameters of PEM fuel cell for solving the mentioned reaction kinetics.

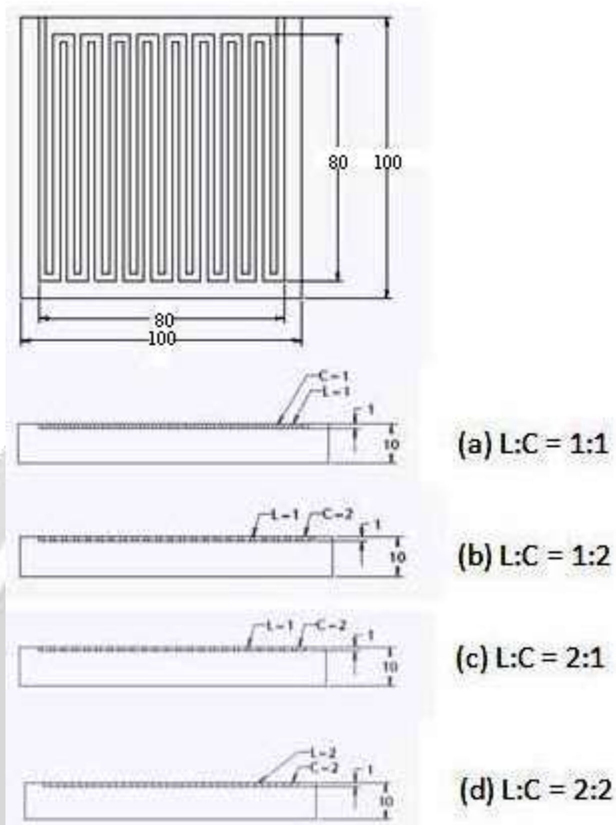

Fig -1 Various landing to channel width (R: C) (a) 1:1 (b) 1:2 (c) 2:1 and (d) 2:2 of serpentine flow field of 64 cm2 active area of PEM fuel cell

2.2 Numerical Modeling

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 be 10000 A/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.
Optimization by Taguchi method has been used to find out the most optimum combination among the various input parameters which would result in getting the maximum possible output which cause the performance enhancement of PEM fuel cell. In this 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 design parameter like landing to channel ratios on serpentine flow field design (L: C-1:1, 1:2, 2:1 and 2:2) and the operating parameters like pressure (1, 1.5, 2 and 2.5 bar), operating temperature (313, 323, 333 and 343 K), anode and cathode stoichiometric ratios of reactants as (S/F) 3, 3.5, 4 and 4.5.

3. RESULTS AND DISCUSSION

Based on L16 orthogonal array, the optimized inputs were given to the 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.

Table 1. Factors, levels, power density and S/N ratio for 16 runs of optimization

Run	R:C	Pressure	Temperature	Stoi.Ratio	Power Density (W/cm2)	S/N Ratio
1	1x1	1	323	3	0.101684	-19.8549
2		1.5	333	3.5	0.134145	-17.4485
3		2	343	4	0.155624	-16.1585
4		2.5	353	4.5	0.162544	-15.7806
5	1x2	1	333	4	0.117038	-18.6335
6		1.5	323	4.5	0.128949	-17.7916
7		2	353	3	0.149088	-16.5312
8		2.5	343	3.5	0.159842	-15.9262
9	2x1	1	343	4.5	0.102134	-19.8166
10		1.5	353	4	0.117062	-18.6317
11		2	323	3.5	0.100254	-19.978
12		2.5	333	3	0.100481	-19.9583
13	2x2	1	353	3.5	0.148073	-16.5905
14		1.5	343	3	0.144675	-16.7921
15		2	333	4.5	0.133062	-17.5189

16		2.5	323	4	0.119379	-18.4614
Average S/N Ratio						-17.867

The landing to channel width ratio of 1:1 for serpentine flow field has shown maximum power densities of 0.163 W/cm^2 and minimum power densities of 0.102 W/cm^2 respectively. Similarly for L:C of 1:2 and 2:1 having maximum power density of 0.159 W/cm^2 and 0.117 W/cm^2 respectively. The minimum power densities for the same L:C ratios have 0.117 W/cm^2 and 0.100 W/cm^2 respectively. For the landing to channel width ratio of 2:2 has shown maximum power density of 0.148 W/cm^2 and power density of 0.119 W/cm^2.

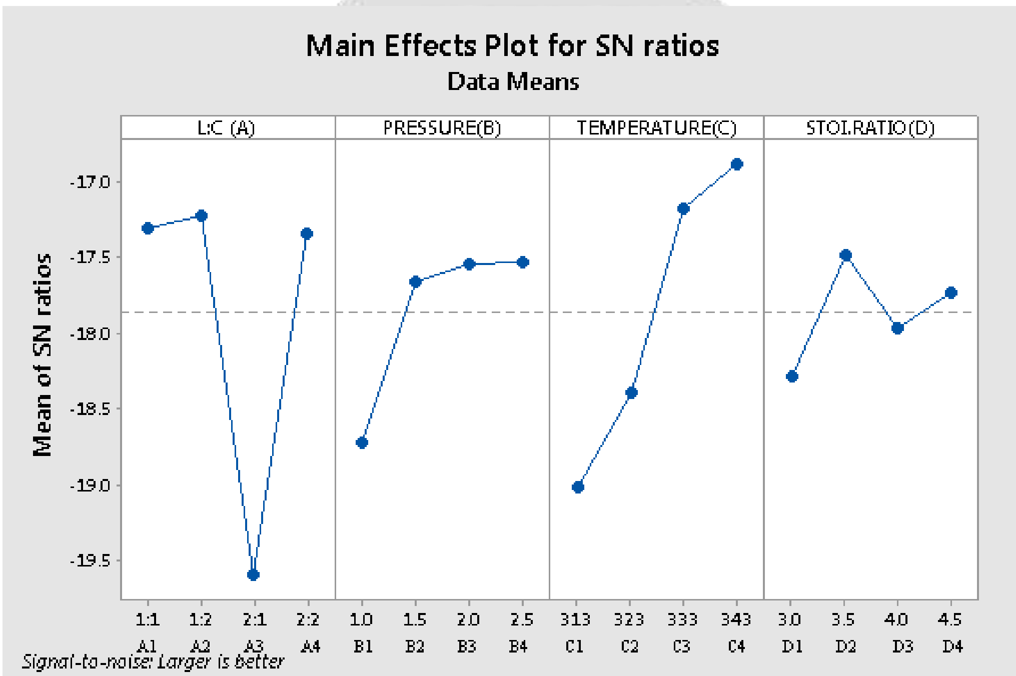

Fig .2. Mean S/N ratio plot for L:C (A1-A4),Pressure (B1-B4),Temperature (C1-C4), Stoi.Ratio (D1-D4)

Table 2. Mean S/N ratios, Delta and Rank for each level of factors

Factors	Level 1	Level 2	Level 3	Level 4	Delta	Rank
Landing to Channel width (L:C)	-17.31	-17.22	-19.6	-17.34	2.38	1
Pressure (bar)	-18.72	-17.67	-17.55	-17.53	1.19	3

Temperature (K)	-19.02	-18.39	-17.17	-16.88	2.14	2
Stoi.Ratio	-18.28	-17.97	-17.97	-17.73	0.8	4

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.2.

It has been observed from the Table 3, L:C has contributed maximum of 56.4 % followed by operating pressure 26.47 %, operating temperature and stoichiometric ratio of the reactants has contributed as 3.22 and 0.06% respectively of the total PEM fuel cell performance. Also the combined effect of combination of pressure with temperature and pressure with R:C has shown 0.77% and 9.21 % respectively contributing to peak power performance of the PEM fuel cell.

Table 3. The percentage contribution of individual parameters of serpentine flow field

Factors	DOF	Sum of squares	Variance	F-test	P-Test	Contribution (%)
Pressure	2	0.000846	0.00042	71.02	0.082	26.47
Temperature	2	0.000124	0.00006	10.4	0.387	3.22
Stoichiometric ratio	2	0.000026	0.00001	2.17	0.967	0.06
R:C	3	0.002663	0.00089	74.48	0.013	56.40
Pressure & Temperature	1	0	0.00000	0.02	0.913	0.77
Pressure & R:C	3	0.000465	0.00016	13.01	0.072	9.21

Error	2	0.000024	0.00001			3.87
Total	15	0.007321	0.001552667	171.1	2.434	100

It was concluded that the design parameter such as, landing to channel ratio of serpentine flow field having -1:2 as A2, and the operating parameters like pressure - 2.5 bar as B4, temperature - 343 K as C4, Stoichiometric ratio of inlet mass flow rate - 3.5 as D2 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 2. . 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, landing to channel width (L:C) of serpentine flow field, operating temperature, stoichiometric ratio of inlet mass flow rate respectively. The percentage contribution of individual parameters, P-test and F-test on the serpentine flow fields for the performance of PEM fuel cell has been shown in the Table 3.

4. CONCLUSIONS

Based on the investigation made by Taguchi method of optimization, with different parameters on serpentine flow field of 64 cm2 active area of PEM fuel cell the following observation has been made.

- The maximum power density of optimizing the four different parameters on serpentine flow field of 64 cm^2 active area of PEM fuel cell using Minitab 17 provides 0.163 W/cm^2 from L:C-1:1 with 2.5 bar operating pressure, 353 K temperature and 4.5 stoichiometric ratio of inlet reactant gases and R^2 value was arrived 99.67 %.
- The combined effect of all the parameters exhibited a different response compared to their individual effects on the total performance of the PEMFC.
- The effect of operating and design parameters was affecting the performance of PEM fuel cell considerably.

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