International Journal of Theoretical and Applied Mechanics.
ISSN 0973-6085 Volume 12, Number 3 (2017) pp. 523-532
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Optimisation of 16cm^2 Single Pass Serpentine Flow Channel of PEMFC Using Taguchi Method

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Abstract

The Proton Exchange Membrane Fuel Cell (PEMFC) performance depends on the design and operating parameters like 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 such as pressure, temperature, stoichiometric ratio of inlet reactant mass flow rate and various landing to channel width (L:C) 1:1, 1:2, 2:1 and 2:2 on serpentine flow channel of 16 cm^2 active area of the PEMFC was studied. Creo Parametric 2.0 and CFD Fluent 14.5 software packages were used to create the model and simulation of PEMFC. The analysis was carried out on the various parameters by Ansys Fluent CFD and optimization was done by Taguchi method using Minitab 17 software. From the optimization study, the L: C- 1:2 has maximum influence on PEMFC performance and square of response factor (R2) was achieved by Taguchi method as 97.90 %.

Keywords- Taguchi method; Optimization; Design parameters; Operating parameters; Square of response factor.

I. INTRODUCTION

The PEMFCs are being established for commercial applications in the areas of transportation and back-up power due to the negligible emission of pollutants, such as SOx, NOx, particulates [1]. It is Eco-friendly power source suitable for powering both portable devices and mobile application due to their high energy density and lower operating temperature range [2]. The PEMFC consists of polymer solid electrolyte membrane sandwiched between an anode and cathode. However, water and heat is the by-product of electrochemical reaction on cathode flow channel and partial pressure of water vapour causes condensation of water on anode flow channel. The water management of PEMFC has become an important task, whereas too much of water accumulation causes "flooding" or too little water causes dryness of membrane can adversely impact the performance and lifetime of PEMFCs. 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 loss, such as non-uniform concentration, current density distributions, high ionic resistance due to dry membrane and high diffusive resistance due to the flooding on the cathode which was addressed by Owejan et al. [3] and Nattawut Jaruwasupanta & Yottana Khunatorna [4]. 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.

The numerical analysis were carried out with six different cross-sections of the Channel (square, triangle, parallelogram 14^o, parallelogram 26^o, trapezium and inverted trapezium) of 1.25 cm^2 active area with a constant cross sectional area of 0.01 cm^2 of single pass PEM fuel cell by lakshminarayanan et al [5]. It was concluded that, square flow channel of single pass PEM fuel cell having a peak power density of 1.133 W/cm^2 @ 2.834 A/cm^2 & 0.4 V .The effect of the various parameters and various landing 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) effective area was analyzed numerically by lakshminarayanan et al [6].He concluded that the maximum power densities of 0.658, 0.642 and 0.596 W/cm^2 were obtained in the L: C of 1:1, 1:2 and 2:2, respectively. However, operating parameters like pressure, temperature and inlet mass flow rate of reactants influenced the performance of PEMFC significantly. The increasing of inlet pressure improved the consumption of reactants and more homogeneous distribution. The effect of channel design also changed the consumption of reactants and consequently increases water production by Zeroual et al. [7]. 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 [8]. A single channel PEMFC with ten operating and design parameters were optimized using Taguchi method for enhancing PEMFC performance by Karthikeyan et al. [9]. 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 [10].

Kanani et al. [11] investigated the effects of operating conditions (cathode and anode stoichiometry, gas inlet temperature and cathode relative humidity) for serpentine flow channel on the performance of the PEMFC 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 [12]. They concluded that the optimum working conditions were found to be 5 bar of system pressure, 75°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 evident that there is a need for immediate attention towards optimizing the simultaneous influence of operating and design parameters for the performance of the PEMFC using CFD Fluent 14.5 and MINITAB 17 software packages. 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 16 cm^2 active area of PEMFC are studied and influence their performance were compared.

II. MODEL DEVELOPMENT

Three dimensional (3-D) PEMFC model with serpentine flow channel of various landing to channel width configurations were created by Creo Parametric 2.0 as shown in Fig.1.

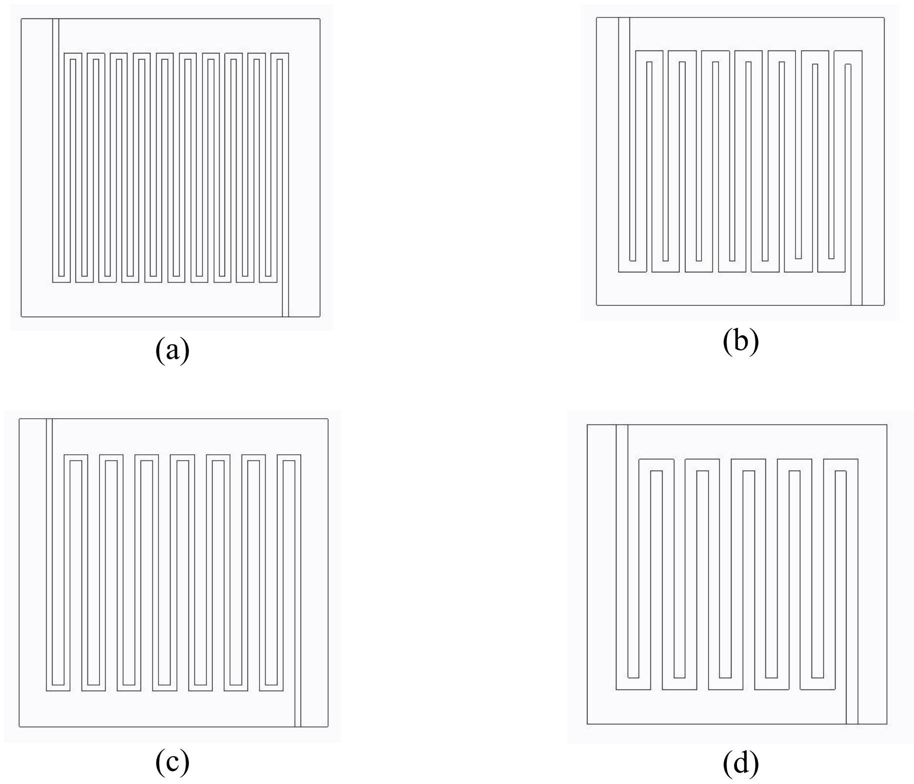

Fig.1. Various landing to channel width (L: C) (a) 1:1 (b) 1:2 (c) 2:1 and (d) 2:2 of serpentine flow channel of 16 cm^2 active area of PEMFC

The modeling was done by creating individual parts of the PEMFC 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 assignments of zones for various parts were done by Workbench 14.5. 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 (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	40	40	10	Solid
2	Anode & Cathode catalyst			0.08	Fluid
3	Membrane			0.127	Fluid
4	GDL anode & cathode			0.3	Fluid

A. Meshing on PEMFC

After geometry building, the next step was discretization done by ANSYS 14.5 ICEM software. The meshing method was used as Cartesian grid, which helps in the formation of hexahedral mesh to get accurate results. Hence the entire cell was divided into finite number of discrete volume elements or computational cells to solve the equations associated with the fuel cell simulation. Split block method used for blocking and meshing was done with Cartesian method. 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.

B. Governing Equations

The simulation 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 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 flow as laminar, fluid as incompressible, thermo physical properties as constant and the porous GDL, two catalyst layers and the membrane as an isotropic.

C. Solver

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.

III. TAGUCHI METHOD

Taguchi method can be used to find out the most optimum combination among the input parameters (Design and Operating) which will result in getting the maximum possible output which cause the performance enhancement of PEMFC. 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 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 cathode side was 3.33E-06 kg/s.

IV. RESULTS AND DISCUSSION

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 numerical study using CFD Fluent 14.5 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.

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	0.335	-9.4991
2		1.5	333	3.5	0.402	-7.91548
3		2	343	4	0.413	-7.681
4		2.5	353	4.5	0.380	-8.40433
5	1x2	1	333	4	0.325	-9.76233
6		1.5	323	4.5	0.365	-8.75414
7		2	353	3	0.306	-10.2856
8		2.5	343	3.5	0.422	-7.49375
9	2x1	1	343	4.5	0.261	-11.6672
10		1.5	353	4	0.281	-11.0259
11		2	323	3.5	0.319	-9.92419
12		2.5	333	3	0.350	-9.11864

13	2x2	1	353	3.5	0.270	-11.3727
14		1.5	343	3	0.339	-9.39601
15		2	333	4.5	0.385	-8.29079
16		2.5	323	4	0.376	-8.49624
Average S/N Ratio						-9.31796

The landing to channel width ratio of 1:1 for serpentine flow field has shown maximum current and power densities of 0.826 A/cm^2 and 0.413 W/cm^{2}respectively and minimum current and power densities of 0.706 A/cm^2 of and 0.335 W/cm^{2}respectively. Similarly for R:C of 1:2 and 2:1 having maximum current density of 0.938 A/cm^2 and 0.737 A/cm^{2}respectively, and the power density of 0.422 W/cm^2 and 0.35 W/cm^2 respectively. The minimum current and power densities for the same R:C ratios have 0.764 A/cm^2 and 0.697 A/cm^2 & 0.306 W/cm^2 and 0.261 W/cm^2 respectively. For the rib to channel width ratio of 2:2 has shown maximum current density of 0.855 A/cm^2 and power density of 0.385 W/cm^2 and minimum current density of 0.635 A/cm^2 and power density of 0.27 W/cm^2. The optimization was performed for "Larger the Better" type of Taguchi method since 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.

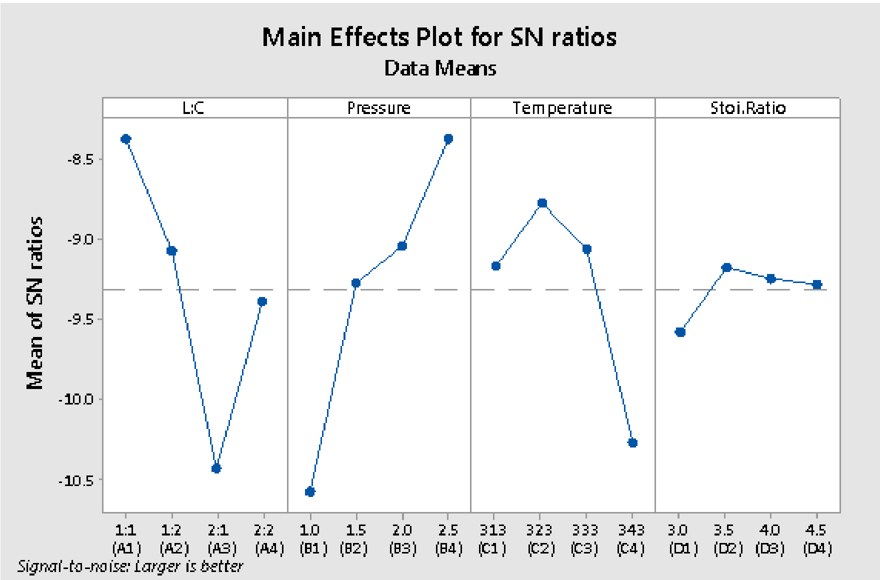

Fig .3. Mean S/N ratio plot for L:C (A1-A4),Pressure (B1-B4),Temperature (C1-C4), Stoi.Ratio (D1-D4)

It was concluded that the design parameter such as, landing to channel ratio of serpentine flow channel having -1:1 as A1, and the operating parameters like pressure - 2.5 bar as B4, temperature - 323 K as C3, Stoichiometric ratio of inlet mass flow rate - 3.5 as D2 were the optimum parameters to show the better PEMFC 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. It was found that pressure was the predominant factor affecting the performance of PEMFC. The other parameters were also influencing the performance of PEMFC to a considerable extent such as, landing to channel width (L:C) of serpentine 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 serpentine flow fields for the performance of PEMFC has been shown in the Table 5.

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
Landing to Channel width (L:C)	-8.375	-9.074	-10.434	-9.889	2.059	2
Pressure (bar)	-10.575	-9.273	-9.045	-8.378	2.197	1
Temperature (K)	-9.168	-8.772	-9.059	-10.272	1.5	3
Stoi.Ratio	-9.575	-9.177	-9.241	-9.279	0.398	4

It has been observed from the Table 5, operating pressure has been shown to be 50.67 % contribution on peak power performance of the PEMFC for the serpentine flow field. Similarly for the operating temperature, the stoichiometric ratio of the reactants and L:C has contributed 16.75 %, 1.62 % and 13.05 % respectively of the PEMFC performance. Also the combined effect of combination of pressure with temperature and pressure with R:C has shown 2.31 % and 0.57 % respectively contributing to peak power performance of the PEMFC.

Table 5. The percentage contribution of individual parameters of serpentine flow channel

Factors	DOF	Sum of squares	Variance	F-test	P-Test	Contribution (%)
Pressure	2	0.004712	0.002356	36.17	0.411	50.67
Temperature	2	0.001732	0.000866	13.3	0.373	16.75
Stoichiometric ratio	2	0.000403	0.0002015	3.09	0.694	1.62
L:C	3	0.002111	0.000704	5.4	0.16	13.05
Pressure & Temperature	1	0.000029	0.000029	0.22	0.684	2.31
Pressure & R:C	3	0.000316	0.0001053	0.81	0.595	0.57
Error	2	0.000261	0.0001305	-	-	15.03
Total	15	0.012385	0.004392	58.99	2.917	100.00

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 serpentine flow channel of 16 cm^2 active area of PEMFC using Minitab 17 provides 0.372 W/cm^2 and R^2 value was arrived 97.90%. The optimum power density 0.422 W/cm^2 was obtained from L:C-1:2 with 2.5 bar operating pressure, 343 K temperature and 3.5 stoichiometric ratio of inlet reactant gases of 16 cm^2 active area of the CFD PEMFC model. The effect of operating and design parameters was affecting the performance of PEMFC more significantly.

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