ISSN: 0974-5823 Vol. 6 No. 3 October-December, 2021

International Journal of Mechanical Engineering

Effect of aspect ratio on performance of six passes serpentine PEMFC with 70 cm^2 active area

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Abstract-

Various operating conditions such asstoichiometric ratio, pressure, temperature, relative humidity of reactants, and design parameters like aspect ratio, flow channel shape, depth etc influence the performance of PEMFC. This work investigates the performance of six pass serpentine flow field aspect ratios of 1 x 1, 1 x 2, 2 x 1 and 2 x 2 on PEMFC with 70 cm^2 active area with 2 bar and 353 K as the operating pressure and operating temperature respectively both numerically and experimentally. The performance of these flow channels when assessed numerically reveal that the PEMFC with aspect ratio 2 x 2 has a maximum power density of 0.4324 W/cm^2 and a peak current density of 1.081 A/cm^2. The corresponding values obtained during experimental validation were 0.392 W/cm^2 and 0.98 A/cm^2 which were in close correlation with the numerical results. This flow channel was also tested for four hours of continuous operation and was found to perform well due to lower water lodging.

Keywords- Serpentine, aspect ratio, numerical analysis, experimental validation, PEMFC, water lodging.

I. INTRODUCTION

The environmental impacts of non-renewable power sources and energy scarcity in many countries, focuses on renewable energy. Proton Exchange Membrane Fuel Cells (PEMFCs) are seen as a viable alternate source for energy due to their high energy density and lower operating temperature range (30ºC - 70ºC) [1]. The PEMFC consists of proton exchange membrane (Nafion) placed between two electrodes namely anode and cathode. The loading of platinum on anode and cathode sides of the membrane enhances their catalytic activity on hydrogen oxidation reaction (HOR) and oxygen reduction reaction (ORR) respectively at the interface between membrane and catalyst. This electrochemical reaction produces electricity along with water and heat as by-products, hence, the management of water and heat is vital to enhance the performance of PEMFC systems. Partial pressure of water vapor causes condensation and accumulation of water on cathode flow channel whereas too little water causes dryness of membrane. Both can adversely impact the performance and lifetime of PEMFCs. Proper design of flow channel can enhance the performance of PEMFC [2,3] by reducing losses, such as, non-uniform concentration, current density distributions, high ionic resistance due to dry membrane, or high diffusive resistance due to the flooding on the cathode [4,5]. So the critical issue in PEMFCs can be resolved through the appropriate design of flow channels through effective removal of water from flow field plates [6]. Thus, identifying the proper flow field design is very important while designing the PEMFC. The influence of impact of flow channel path length on PEMFC flow field design has been studied and it was concluded that serpentine flow channel has better performance [7-9]. Hence serpentine flow channel is used in this study. The influence of aspect ratio is inevitable in the performance of PEMFC [10]. The Effect of electrical resistance under land and channel widely influences the performance of PEMFC [11]. Hence, an effort has been made to study rib to channel width hereinafter referred as aspect ratio of R:C -1:1, 1:2, 2:1 and 2:2 in 70 cm^2 six pass serpentine PEMFC. This work studies the influence of rib to channel width on the performance of PEMFC both numerically and experimentally which has been not been addressed in previous studies.

For numerical investigations, standard physical conservation equations such as mass, momentum, charge, and energy equations are considered. A successful model which can predict the performance of a fuel cell is designed. The influence on performance of the different aspect ratios considered are weighed against high current and peak power density, proper temperature distribution and optimum water management [12]. The best flow field design selected from numerical analysis is fabricated and experimentally validated.

II. NUMERICAL MODELLING

Three dimensional (3-D) PEMFC model for serpentine flow channel of different R:C of 1:1, 1:2, 2:1 and 2:2 configurations were developed by 'ProE wildfire 5' and meshed by using ICEM 14.0 [13] (a module of ANSYS 14.0). The assignment of zones for various parts were done by Workbench 14.0 the same along with dimensions are given in table 1. The modeling was done by creating individual parts of the PEMFC such as the anode and cathode flow channel, Gas diffusion layer (GDL) in the anode and the cathode, solid polymer electrolyte membrane (Nafion), catalyst layer at the anode and the cathode. In order to solve the myriad of equations associated with a fuel cell simulation, the entire cell is divided into a finite number of discrete volume elements. Geometrical models with rib width to channel width of 1:1, 1:2, 2:1 and 2:2 form the basis for creating a computational mesh. The grid independent study has been carried for all the models [14,15] and obtained optimum configurations of nodes and elements are considered for further numerical analysis.

Table 1. Dimensions and zone type of fuel cell

S. No	Part Name	Width (mm)	Length (mm)	Thick-ness (mm)	Zone Type
1	Catalyst	70	100	0.3	Fluid
2	Flow channel	70	100	10	Solid
2	Membrane	70	100	0.08	Fluid
3	GDL	70	100	0.12	Fluid

A control volume approach based on commercial solver FLUENT 14.0 is used to obtain reaction kinetics of PEMFC through equations like conservation of mass, momentum, energy, species concentration, Butler–volmer equation, Joule heating reaction and Nernst equation are solved. This model considers that the state is steady, the inlet gases are ideal, the system is isothermal, the flow is laminar, the fluid is incompressible, the thermo physical properties is constant and the GDL is porous, the two catalyst layers and the membrane are isotropic. Nonslip boundary condition is assumed at the walls. The operating pressure and temperature is taken as 2 bar and 353 K respectively at the exit of cell. The species concentration on anode side for H_2, O_2, and H_2O are 0.8, 0, and 0.2 respectively similarly, those at the cathode side are 0, 0.2 and 0.1 respectively. The flow of hydrogen and oxygen is in opposite directions. The rate at which reactants are fed, $\dot{n}_{H_2}$ is given by

$$\dot{n}_{H_2} = \frac{iA}{nF}$$

Where, i is current density in $\frac{A}{m^2}$, A is the total active area of all fuel cells in a stack put together in m^2, n is the number of moles of electrons transferred during the electrochemical reaction, F is the Faraday's constant.

Open circuit voltage was set as 0.95 V. Because the anode voltage was grounded, the cathode voltage has been varied from 0.1 V to 0.95 V, for solving of reaction kinetics in order to get current flux density and H_2, O_2 and H_2O fractions along the flow field design. Multigrid settings and termination restriction value are taken as F-Cycle and 0.001 for all equations. H_2, O_2, H_2O and water saturation electric and proton potential is set at 0.0001 and Bi-Conjugate Gradient Stabilization method or Krylov-space method (BCGSTAB) is opted. The complete results for the same are given in Annexure 1.The maximum power density obtained by numerical analysis for R:C ratios of 1:1 and 2:2 are 0.208 W/cm^2 and 0.432 W/cm^2 at 0.4 V respectively. Whereas the maximum power density for R:C ratios of 1:2 and 2:1 are 0.301 W/cm^2 and 0.307 W/cm^2 at 0.45 V respectively. It is evident that, the six pass serpentine flow channel with R:C of 2:2 has 28.9% more power output than its closest variant that is R:C ratio 2:1. The response of voltage and power density as dependant variables to current density as an independent variable i.e., the V-I and P-I curves are shown in figures 1 and 2 respectively.

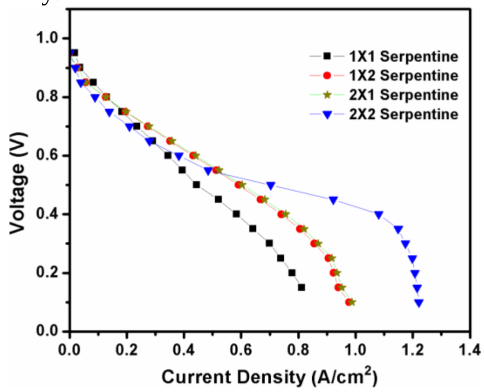

Fig. 1 Voltage Vs Current Density (V-I Curve) for various R:C

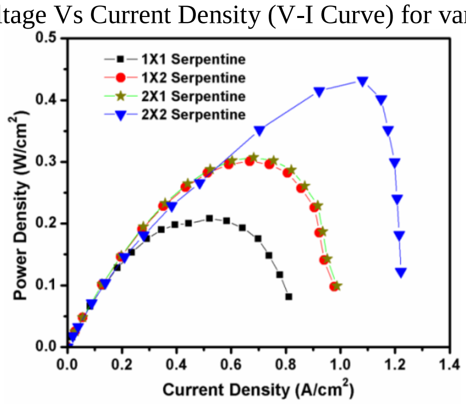

Fig. 2 Power Density Vs Current Density (P-I Curve) for various R:C

H_2 and O_2 concentrations, H_2O accumulation, their distribution on flow channel and current flux density distribution at their peak power densities are as follows.

The concentration of hydrogen decreases from the inlet to outlet as it is consumed on the way due to the electrochemical reaction that is taking place this variation is shown in figure 3. The water molar fraction distribution in the cell is shown in figure 4. The concentration of water inside the fuel cell strongly depends on consumption of the reactants. Production of water is higher in the cathode catalyst layer in which the electrochemical reactions take place. The water produced on the surface level of catalyst at the cathode side diffused through the membrane and the GDL. The diffusion of water is towards outlet, which is a positive sign of water management as the water formed will to move out.

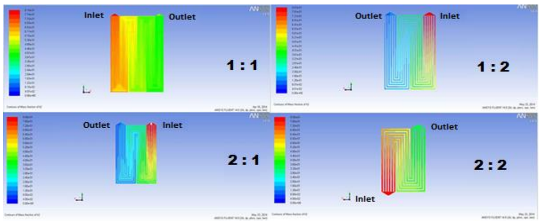

Fig. 3 Hydrogen distribution through the anode side flow channel for various R:C

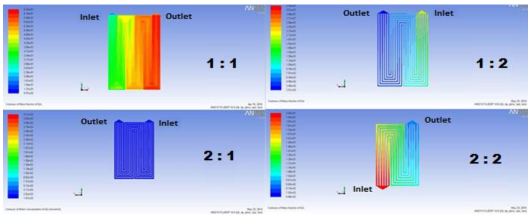

Fig. 4 Water distribution through the anode side flow channel for various R:C

The variation of mass fraction of O_2 along the flow channel and H_2O distribution on cathode flow field design are shown in figures 5 and 6 respectively. To understand H_2O accumulation in fuel cell it is recommended to relate the rate of hydrogen and oxygen consumption with liquid water accumulation by which one can easily deduce that water accumulation increases gradually towards outlet of the cathode flow channel.

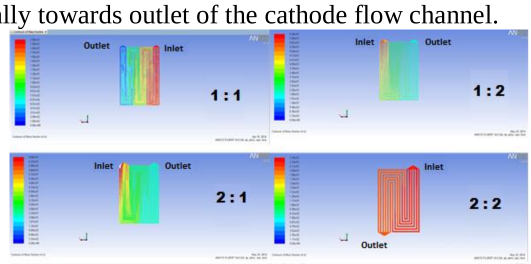

Fig. 5 Oxygen distribution through the cathode side flow channel for various R:C

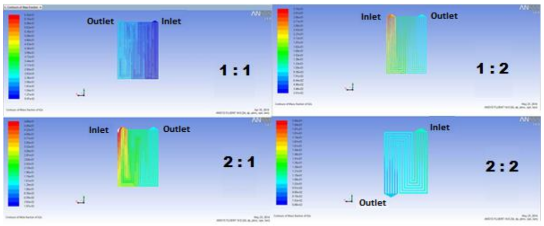

Fig. 6 Water distribution through the cathode side flow channel for various R:C

The current flux density distribution on anode and cathode flow channel is shown in figures 7 and 8 respectively. It shows that current flux density magnitude distribution is more uniform throughout the flow channel. This is because species distributions on anode and cathode are more uniform in six pass serpentine flow channel, so ohmic losses have been reduced hence enhancing the performance of PEMFC.

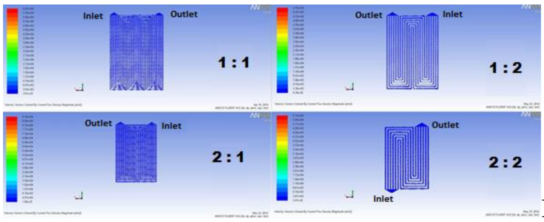

Fig. 7 Current flux density on anode side flow channel for various R:C

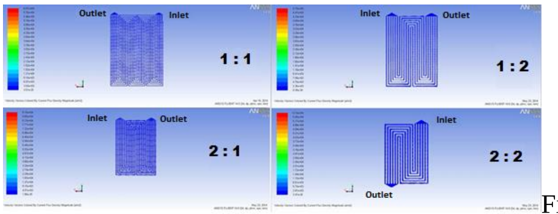

Fig. 8 Current flux density on cathode side flow channel for various R:C

An experimental investigation of 70 cm^2 PEMFC on six pass serpentine flow channel with V-grooved inlet and R:C 2:2 has been carried out to validate the results obtained from numerical analysis as R:C 2:2 revealed peak power density.

III. EXPERIMENTAL INVESTIGATION

The Bio-Logic FCT-50S test station has been used for experimental analysis and this has been interfaced to a computer system using FC-Lab V.5.22 software package. A Gas Diffusion Electrode (GDE) sheet has been used for experimental analysis. This GDE has carbon paper as its GDL or Diffusion Medium and 40% Pt/C as catalyst with a loading of 0.5 mg/cm^2. The Nafion 115 membrane has been sandwiched with GDE of size 7 cm x 10 cm and 70 cm^2 on either side by hot pressing at 130ºC, with a pressure of 50 kg/cm^2 for 3 minutes. High purity hydrogen (99.99%) and oxygen have been used as fuel and oxidant respectively. The gold coated copper plates have been used on anode and cathode as current collectors. The MEA has to be properly humidified in order to ensure that it works at its peak power value. For humidifying the MEA, an activation procedure is done by the application of voltage pulse and current pulse programs. The schematic of the fuel cell test setup is shown in the figure 9.

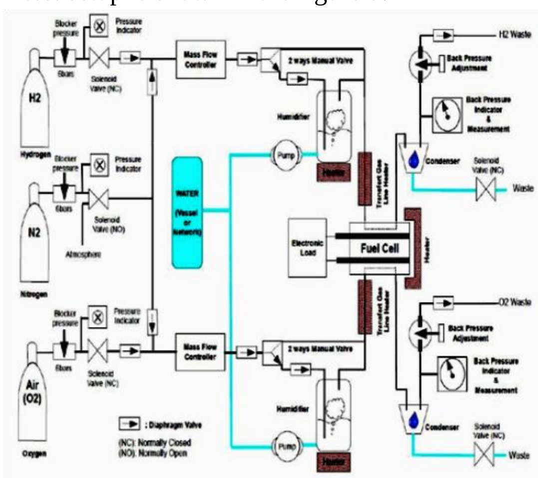

Fig 9. Schematics of the fuel cell test setup

The following operating parameters have been considered for 70 cm^2 PEMFC: cell temperature of 50oC, humidification temperature of the anode and cathode of 80oC, anode and cathode line temperature of 50oC. The experimental setup with software interface is shown in figure 10.

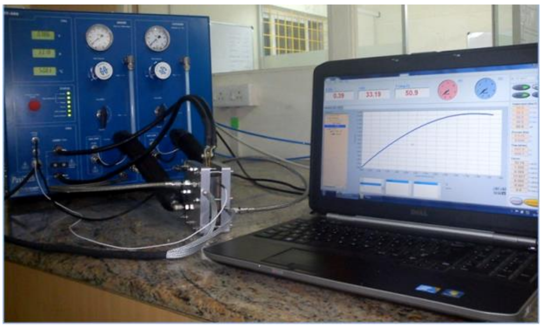

Fig. 10 Experimental setup with software interface

The anode gas and cathode gases are supplied at the rate of 1200 ml/min and 600 ml/min. The anode and cathode stoichiometry has been taken 2.5 respectively.

IV. EXPERIMENTAL RESULTS

The experimental analysis of six pass serpentine flow channel with v-grooved inlet of rib width to channel width of R:C - 2:2 at 2 bar operating pressure and 353 K temperature reveals a maximum power density of 0.392 W/cm^2 for the same operating conditions.

The variation in current density between predicted numerical model and the experimental results are 9.34%. This may be due to entropy of experimentation and also because in the numerical model all operating parameters are completely controlled but during experimentation a quasi controlled atmosphere can only be achieved due to limitations of the components used. The values for current density and power density were obtained after four hours of operation.

V. CONCLUSION

The primary conclusion that can be drawn from the results is that the six pass serpentine flow channel with v-grooved inlet having an aspect ratio 2 : 2 [17-20] can perform better than the other variants studied in terms of maximum current density. Secondarily the numerical model developed is in close coordination with the experimental results and hence can be used to predict the performance of PEMFC.

Although the current density of PEMFC with an aspect ratio 1 : 1 was initially better its performance reduced over time this is due to accumulation of water in flow channels. The average size of the droplets formed is slightly greater than 1 mm causing blockage in flow channels and reducing the intensity of the reaction. Whereas such droplet formations do not cause much of a hindrance in an aspect ratio 2 : 2 make it perform well during long hours of operation.

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Annexure 1 Preformance Six Pass Serpentine Flow Channel with Various Ribs to Channel Width

Voltage (V)	1:1		1:2		2:1		2:2	
	i (A/cm^2)	P (W/cm^2)	i (A/cm^2)	P (W/cm^2)	i (A/cm^2)	P (W/cm^2)	i (A/cm^2)	P (W/cm^2)
0.10	0.812	0.081	0.977	0.098	0.987	0.099	1.221	0.122
0.15	0.778	0.117	0.940	0.141	0.952	0.143	1.215	0.182
0.20	0.739	0.148	0.923	0.185	0.935	0.187	1.207	0.241
0.25	0.699	0.175	0.905	0.226	0.917	0.229	1.198	0.300
0.30	0.642	0.193	0.856	0.257	0.869	0.261	1.174	0.352
0.35	0.584	0.204	0.806	0.282	0.820	0.287	1.149	0.402
0.40	0.521	0.208	0.740	0.296	0.755	0.302	1.081	0.432
0.45	0.445	0.200	0.668	0.301	0.682	0.307	0.922	0.415
0.50	0.395	0.198	0.591	0.296	0.603	0.302	0.703	0.352
0.55	0.345	0.190	0.513	0.282	0.523	0.288	0.484	0.266
0.60	0.291	0.175	0.432	0.259	0.441	0.265	0.382	0.229
0.65	0.236	0.153	0.351	0.228	0.358	0.233	0.279	0.181
0.70	0.183	0.128	0.273	0.191	0.278	0.195	0.209	0.146
0.75	0.130	0.098	0.195	0.146	0.197	0.148	0.139	0.104
0.80	0.083	0.066	0.126	0.101	0.127	0.102	0.089	0.071
0.85	0.036	0.031	0.056	0.048	0.056	0.048	0.039	0.033
0.90	0.018	0.016	0.028	0.025	0.028	0.025	0.020	0.018
0.95	0	0	0	0	0	0	0	0