Review on Design and Development of Proton Exchange Membrane Fuel Cell

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Abstract— Proton exchange membrane fuel cells (PEMFC), are a type of fuel cell being developed for transport, stationary and portable applications. PEM Fuel Cell performance depends on many factors, including the operating conditions, transport phenomena inside the cell, kinetics of the electrochemical reaction, MEA assembly and flow channel geometry. For the homogeneous distribution of the reactants all over the catalyst surface through the flow channels, flow patterns or paths machined on the Flow field plates /Bipolar Plates(in case of stack) surfaces to guide the reactants to gas diffusion layer for correct distribution. The incorrect flow distribution may affect the fuel cell stack performance. Thus, the design of more effective flow channels has received considerable attention of the researchers. In this research review numerically as well as experimental investigations of the influence of the channel cross-section is presented as a design parameter of flow channel geometry on the performance of a PEM fuel cell especially with serpentine flow field (SFF) design.

Key words: PEM Fuel Cell, Design Parameter, Flow Field, Serpentine

I. INTRODUCTION

In 1989 the fuel cell discover by Sir William Grove. Proton exchange membrane fuel cells were first used by NASA in 1960's as part of the Gemini space program. This fuel cell used pure hydrogen and air/oxygen as a reactant gases. NASA interested to future development of Fuel cells because of the energy crisis in 1973.

Due to the increasing world concern about the environmental pollution and the depletion of fossil fuel reserves, the solutions for the generation of clean energy became vital. In the last decade, fuel cells appear to be one of the most suitable alternatives for generation of clean energy and among them, PEM fuel cells seem to be one of the most reliable ones. Some of the PEMFC advantages over other types of fuel cells are their easy implementation and their longer lifetime. Furthermore, their low operation temperature, high power density, fast start-ups, soundness of the system and low emission have encouraged the interest of various industry sectors to open up new fields of application for these fuel cells, including the motor industry, the stationary power generation, portable applications, etc.

Although there are many factors involved in the performance of a PEMFC such as the operating conditions, the transport phenomena, the kinetics of the electrochemical reactions, Flow field geometry.

A. *Working of PEM fuel cell*

Fuel cell is electrochemical device which converts chemical energy of reaction into the electrical energy. It consists of an electrolyte with anode (negative electrode) and cathode (positive electrode) on either side, when H_2 gas is fed to anode the H_2 is split into protons and electrons on anode catalyst layer the protons is allow to flow through the electrolyte to the cathode side but electrons are not allow to flow though the electrolyte so electrons are flow through the external circuit where electricity (discharge) are produced. When electrons and protons flow from anode to cathode simultaneously the Oxygen(from air) gas is fed to cathode after then electrons proton and O^{2-} react at cathode catalyst layer and produce water and heat as a byproduct. The fuel cell produces electricity till the fuel is supplied continuously. Fig.1 shows the schematic diagram of PEM fuel cell.

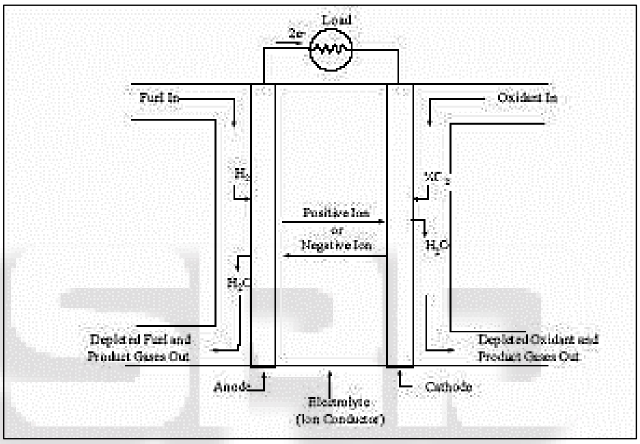

Fig. 1: Schematic PEM Fuel Cell

B. *Components of PEM Fuel Cell*

1) *Electrolyte Membrane*

Fuel cell membrane have relatively high proton conductivity, it provide a barrier to mixing of fuel and reactant gases. It is made of perfluorocarbon-sulfonic acid ionomer (PSA). The main property of the membrane is proton conductivity which is the function of water content and temperature.

2) *Catalyst Layer*

Catalyst layer is essentially made of a thin Platinum or other catalyst layer pressed between the ionomer membrane and a porous electrically conductive substrate. In this electrode catalyst layer electrochemical reaction take place.

C. *Gas Diffusion Layer (GDL)*

GDL plays crucial role in PEM fuel cell, it distribute the reactant gases homogeneously from the flow field to the catalyst layer through it for the electrochemical reaction. It prevents local hotspot and catalyst flooding by removing heat and excess water from the electrode. It is made of carbon fiber material such as carbon fiber paper and woven cloths.

D. *Flow Field Plates*

After the MEA (membrane electrode assembly) has been pulled together, the cell(s) placed in cell to distribute fuel hydrogen and oxidant air/oxygen to the cells evenly. In single fuel cell, there are no bipolar plate (only one-sided flow field plate). In fuel cells with more than one cells, there is typically at least one bipolar plate (flow fields on both side of the plate).

Bipolar plate performs many role in fuel cell. They distribute oxidant and fuel within the cell, separate the individual cells in the stack, collect the current and carry water away from each cell.

In order to simultaneously perform these function, specific plate materials and design are used. Commonly use design can include straight, serpentine, parallel, interdigitated or pin-type flow fields as shown in Fig.2

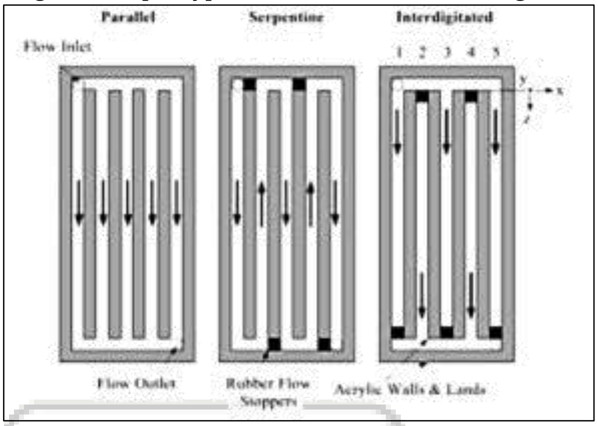

Fig. 1: Various designs of flow field plates

Based upon resistance to corrosion, chemical compatibility, density, cost, electronic conductivity, manufacturability, stack volume/kW, gas diffusivity/impermeability, thermal conductivity, and material strength the materials are chosen. The material most often used are nonporous graphite, titanium, stainless steel and doped polymer. Several composite material has been researched and are beginning to be mass produced.

E. Performance of PEM fuel cell

1) Polarization Curves

These is measure of characterizing a fuel cell performance is through a polarization curve – which is a plot of current density versus cell potential. This current-voltage curve is the most common and effective method for characterizing fuel cell efficiency and typically used for comparing to other published data. The polarization curve shows the V-I relationship with respect to operating condition such as applied load, cell temperature, humidification, and fuel/oxidant flow rate. Figure 3 shows a typical polarization curve for a single Proton Exchange Membrane fuel cell, and the region of importance.

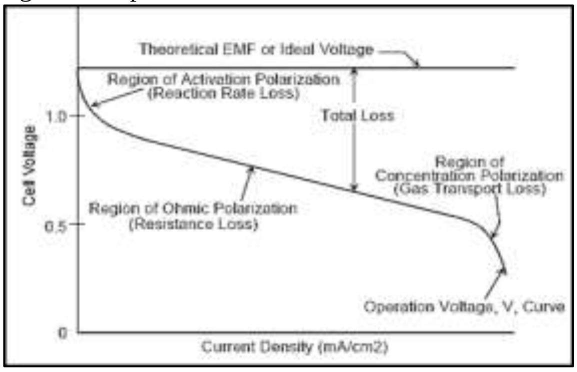

Fig. 3: Polarization curve

As shown in Figure 3, the polarization curve can be separated into three regions:

- The region of activation overpotential,
- The region of ohmic overpotential, and
- The region of concentration overpotential.

II. LITERATURE REVIEW

These are the research reviews subjected to use of various experimental models, Numerical models as well as commercially available CFD packages for design and development of PEM fuel cell and to determine effect of various aspects of serpentine flow field design on the performance of fuel cell.

A. Atul Kumar, Ramana G. Reddy 2003 [1]

They focused on the improvement in the performance by optimizing the flow channel dimensions and shape of the polymer electrolyte membrane fuel cell (PEMFC). They used single-path serpentine flow-field design for studying the effect of channel dimensions on the hydrogen consumption at the anode. They have done simulations for different channel depth, land width and channel width. Range for each of the dimensions (channel depth, land width and channel width) were 0.5 to 4 mm selected. They optimize dimension value for channel width, land width and channel depth and that was close to 1.5, 0.5 and 1.5 mm, respectively for high hydrogen consumptions (~80%), they also studied the effect of channel shapes: triangular and hemispherical shaped cross-section that increase consumption of hydrogen around 9% at the anode.

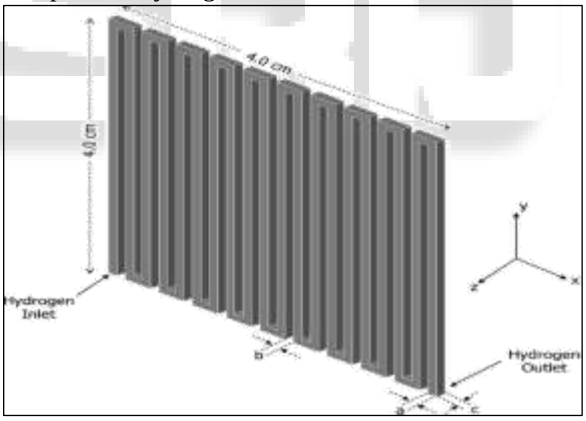

Fig. 2: Serpentine flow-field design in flow field plate showing typical dimensions for channel width (a), land width (b) and channel depth (c).

The model equations were solved using commercial computational fluid dynamics software Fluent® 6.0 with Gambit® as a pre-processor.

The boundary conditions taken as operating temperature was set to 350 K and pressure was set to 2 atm. The mass-flow-inlet of the hydrogen reactant gas was kept constant at 2.5×10^{-7} kg/s for the model which was same for all the simulation cases. They assumed that hydrogen inlet is mass-flow inlet and enters normal to the channel cross-section.

Fig. 4 shows the serpentine flow-field design for the flow field plate with rectangular cross-section channels, showing typical dimensions for channel width, land width and channel depth.

B. S. Shimpalee, J.W. Van Zee 2007 [2]

They considered three geometries in study for investigating the effect of channel/rib width. All geometry had triple channel design with 10 serpentines and the total channels of 30 as shown in Fig- 5.

They considered two operating conditions based on application (I) Stationary application: 80 ºC/70 ºC dew point at 1.2/2.0 Stoichiometry of 40% H2 at anode and Air at cathode respectively; with 101 kPa of system pressure and 70 ºC cell operating temperature, and (II) Automotive application: 75% RH 80 ºC/DRY at 1.3/2.0 stoichiometry of pure H2 at anode and Air at cathode respectively; with 274 kPa of system pressure and 80 ºC cell operating temperature. Co-current flow direction was taken as default in this study.

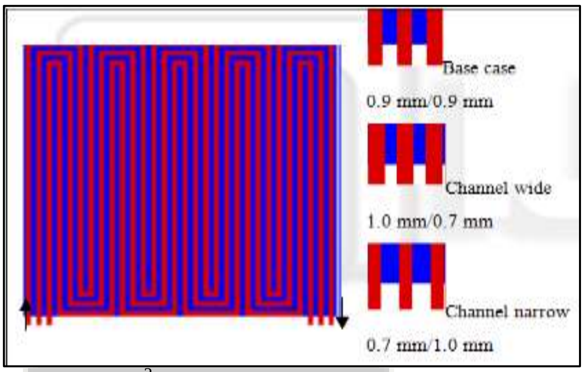

Fig. 3: 25-cm^2 flow-field with three different widths of channel/rib.

They used STAR-CD 3.26 a commercial flow solver based on a control volume technique was used to solve the coupled governing equations. An add-on tool called expert system of PEMFC (ES-PEMFC) version 2.20 that has the requirement of the different source terms for species transport equations, water phase change model, heat generation was solved using electrical loss equations.

They concluded for stationary conditions the result with the channel with 0.7 mm/1.0 mm. channel/rib (narrower configuration) has the highest performance compared to other configurations.

For automotive conditions due to the increase in operating pressure and fuel content, the flow-field 1.0 mm/0.7 mm (wider channel configuration) shows the highest performance compared to others.

C. D.H. Jeon, S. Greenway, S. Shimpalee, J.W. Van Zee 2008 [3]

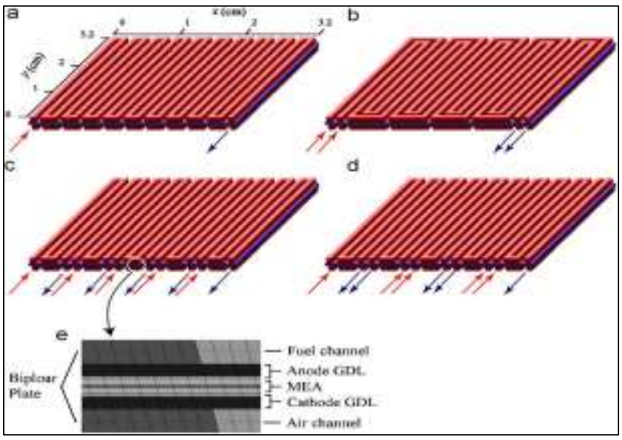

Fig. 4: The 10-cm2 serpentine PEM fuel cells: (a) single channel flow-field; (b) double channel flow-field; (c) cyclic-single channel flow-field; (d) symmetric-single channel flow-field; (e) the detailed schematic of computational domain.

They have done CFD simulation of four 10cm^2 serpentine flow-fields with single channel, double channel, cyclic-single channel, and symmetric-single channel designs in as shown in Fig – 6 to investigate the effect of flow-field design.

(1) single channel with 20 serpentine passes flow-field and (2) double channel with 10 serpentine passes flow-field, and two shorter flow channel length configurations with five inlets and outlets, (3) cyclic single channel with four serpentine flow-fields, and (4) symmetric-single channel with four serpentine flow-fields, were considered. The computational domain includes MEA, GDL, gas channel, and bipolar plate as shown in Fig. - 6(e).

The full-cell models have 10cm^2 of reaction area and a 0:8mm× 1:0mm cross-section. Since the inlet flow rate was controlled by stoichiometric numbers of 1.2/2.0 at anode/ cathode, the total inlet flow velocity varied at each configuration as shown in Table 1. The operating conditions were optimized values from internal experimental studies.

	Single	Double	Cyclic Single	Symmetric Single
High inlet humidity(m/s)				
Anode	2.582	1.291	0.516	0.516
Cathode	7.678	3.839	1.536	1.536
Low inlet humidity(m/s)				
Anode	1.833	0.916	0.366	0.366
Cathode	6.629	3.314	1.326	1.326

Table 1: Inlet Flow Velocity At i_{avg} = 0:6A cm^{-2}

A CFD based on a commercial finite volume technique solver, STAR-CD version 3.26, and an add-on tool modulated to PEMFCs, ES-PEMFC version 2.2, were used to solve the fully coupled governing equations. The structured and uniform grid cells were established. The solution procedure to solve the flow-field was based on SIMPLE algorithm with algebraic multigrid (AMG) method. The number of computational cells was varied with complexity of the model. The total cell size was 0.167 million cells for the single channel, cyclic-single channel, and symmetric-single channel flow-fields, and was 0.24 million cells for the double channel flow-field.

Polarization, local current density distribution, and membrane water content were analyzed for these flow-fields at each humidity condition.

For high inlet humidity, the double channel flow-field was found to have the highest performance (2–3% higher performance than the others) and to have most uniform current density distribution. However, for low inlet humidity, there were little difference on performance and current density uniformity among four serpentine flow-fields.

D. A.P. Manso, F.F. Marzo, M. Garmendia Mujika, J. Barranco, A. Lorenzo 2011 [4]

They numerically investigated the impact of the channel cross-section aspect ratio defined as the ratio height/width on the performance of a PEM fuel cell with serpentine flow field (SFF) design. Various operating parameters such as the local current densities, hydrogen and oxygen concentrations, velocity distributions, liquid water concentration in the membrane and temperature were observed in the PEM fuel cell for 10 aspect ratios that are varying between 0.07 and 15, to understand the channel cross-section aspect ratio effect. The total effective reactive area of the PEM fuel cell (256 mm2) and The channel cross-section area (1.06 mm2) were maintained constant for all cases.

A control volume technique was used based on a commercial program, STAR-CD (version 3.26) along with the expert module for PEMFC (es-pemf version 2.2) to resolve the mathematical model based on coupling the equations for fluid-dynamics (CFD) and specific transport processes and electrochemical reactions of the PEMFC. This software requires source terms to be specified for the species transport and heat generation equations due to electrical losses.

Using bipolar plates with SSF (Serpentine Flow Field) flow channels: 02/30, 03/20, 04/15, 05/12, 06/10, 10/06, 12/05, 15/04, 20/03 and 30/02 as six cases shown in Fig. - 7

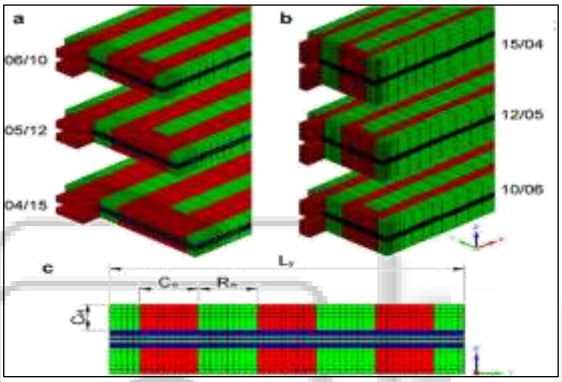

Fig. 5: Geometric configuration of the models analyzed: a) Models with horizontal cross section; b) Models with vertical cross section; c) Diagram of the cross section and parameters; CH: Channel height, CW: Channel width, RW: Rib width, Ly: Width of the reactive area.

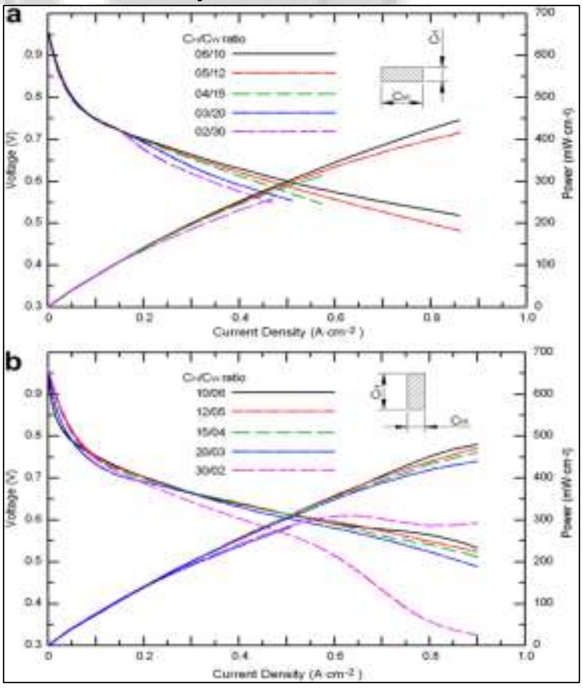

Fig. 6*:* Polarization curves: a) Models with horizontal cross section (06/10, 05/12, 04/15, 03/20 and 02/30); b) Models with vertical cross section (10/06, 12/05, 15/04, 20/03 and 30/02).

Their study concluded that Models with low channel cross-section aspect ratio ($C_H < C_W$) determine a lower overall performance.

On the other hand, models with high channel cross-section aspect ratio ($C_H > C_W$) gives better performance.

E. Kap-Seung Choi, Hyung-Man Kim, Sung-Mo Moon. 2011 [5]

Three different channel heights and widths were compared with the base flow-field design of the serpentine channel whose width is 1mm and 0.34mmin height, each through a detailed numerical study of the distribution of pressure, temperature, local current density and water content.

Seven 25 cm^2 serpentine flow-fields of 5-passes and 4-turnswere numerically simulated, In the present study, CFD programs based on STAR-CD version 4.10, a commercial finite volume technique solver, and ESPEMFC version 2.30, an add-on tool modulated to PEMFCs, were used to solve the fully coupled governing equations. The model assumes a steady state, ideal gas properties, and homogeneous two phase flows. For the solution procedure to solve the flow field, the SIMPLE algorithm was applied with an algebraic multi-grid method.

Numerical simulations were performed to compare the base design of case #1 with the channel heights of cases #2-4 and the widths of #5-7, and the seven geometric parameters applied are listed in Table 2.

Case	Width (mm) (channel/rib/turn rib)	Height (mm)	Cross-sectional area (cm^2)
#1	1.0/1.0/1.25	0.34	0.0170
#2	1.0/1.0/1.25	0.5	0.0250
#3	1.0/1.0/1.25	0.67	0.0335
#4	1.0/1.0/1.25	0.83	0.0415
#5	1.25/0.75/0.94	0.34	0.0212
#6	1.5/0.5/0.63	0.34	0.0250
#7	1.75/0.25/0.31	0.34	0.0297

Table 2*:* Geometry of Cases

Operating conditions of all cases were same H_2/Air on anode/cathode; Stoichiometry 1.5/2.0, inlet temperature 75/75ºC, RH 100/100 was taken.

As the channel height increases, the pressure drop is decreased because of the greater cross-sectional area for gas flow. The cell voltage was decreased with the increase of channel width, and its extent of the reduction is larger than that with the increased channel height.

Their findings in this work could be use to optimize the design of gas flow channel for PEMFC. High cell voltage and uniform current density can be maintained by applying the favorable effects of channel height and channel width that minimize the pressure drop and facilitate the discharge of liquid water.

F. Woo-Joo Yang, Hong-Yang Wang, Young-Bae Kim. 2012 [6]

They investigated operational parameters, geometrical shape and relative humidity and its effect on PEM fuel cell performance in this paper. Specifically, the land ratio of the gas channel and rib as an important factor affecting PEMFC performance as current density distribution is affected by this geometrical characteristic.

A unit cell from the PEMFC stack is considered Fig. 9. The serpentine channel has two bends, and the upper part consists of the cathode, whereas the lower part consists of the anode.

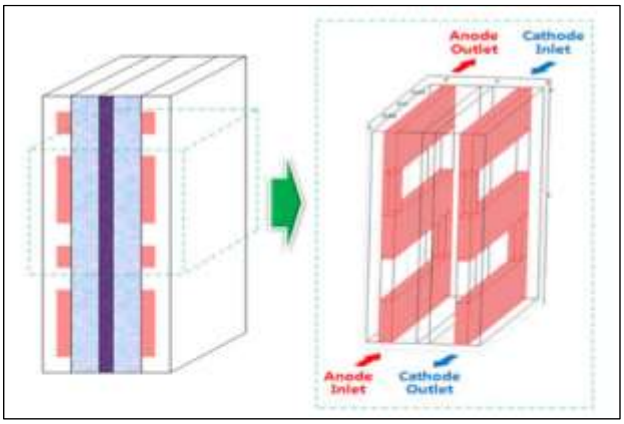

Fig. 7: Schematic illustration for PEMFC 3D model

Three land ratios of channel and rib are considered in the study and their detailed geometries and characteristics are summarized in Table 3.

Model	Total volume (W×H×L)	Rib	Channel	Ratio Rib:Channel
Case #1	10×4.5×20	2	2	1:1
Case #2	8×4.5×20	1	2	0.5:1
Case #3	7×4.5×20	0.5	2	0.25:1

Table 3: Geometry Details (In Mm)

Humidified hydrogen and air were introduced into the anode and cathode channel inlets and their respective mole fractions are determined by the inlet relative humidity. In their study, three different inlet relative humidified hydrogen and oxygen are considered: 100%, 80%, and 60%, respectively. For the numerical analysis of the model.

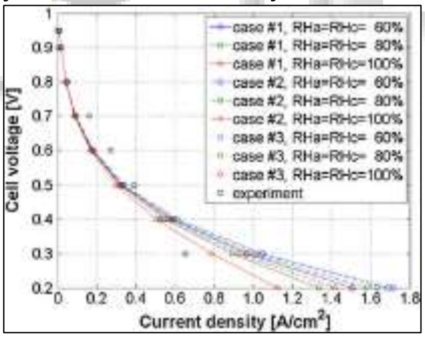

Fig. 8: Polarization curves of four different channel/rib configurations.

The polarization curves obtained for the three land ratio variation cases, along with three relative humidity variations, are shown in Fig. 10. The result clearly shows that the land ratio and inlet relative humidity affect PEMFC performance. To prove the validity of the hypothesis of their study, the published experimental result is also presented in the Fig 10.

With the results from their research it is concluded that different PEMFC performances can be obtained by varying land ratios and inlet relative humidity levels.

G. Luciana S. Freire, Ermete Antolini, Marcelo Linardi, Elisabete I. Santiago, Raimundo R. Passos 2014 [7]

They studied the effect of operational parameters on the performance of PEMFCs by using serpentine flow field channels with different (rectangular and trapezoidal) cross-section shape has been investigated as shown in Fig. 11.

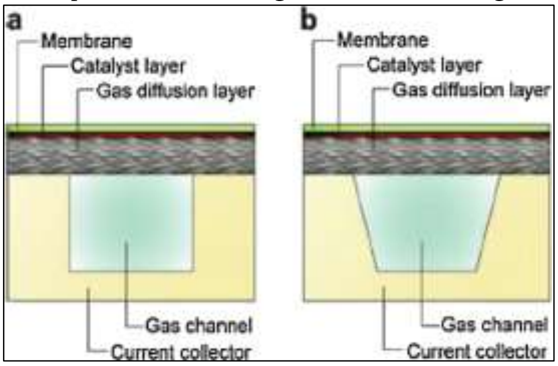

Fig. 9: Cross-sectional views of flow channel geometries. (a):rectangular; (b):trapezoidal.

PEMFC tests were carried out in H_2/O_2 at cell temperatures (T_c) of 80 and 85 ºC; considering that, when fuel cell operating temperature is higher than the gas stream humidification temperatures, the performance of the fuel cell can decrease cathode and anode reactant humidification temperatures (T_{hc} and T_{ha}, respectively) were the same or higher than Tc; each test was expressed as $T_c/T_{hc}/T_{ha}$, and the temperature tested were: 80/80/80, 80/85/95, 85/85/85, and 85/90/100. Cell tests were performed at hydrogen and oxygen pressures of 1 bar. Tests at 80/85/95 ºC were also carried out at H_2 pressure of 2 bar and O_2 pressure of 2 and 3 bar. H_2 and O_2 gas flow was 148 and 200 mL min^{-1}, respectively.

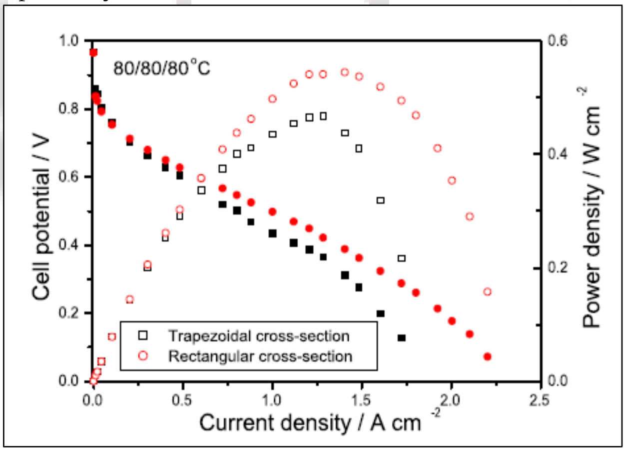

Fig. 10: Polarization and power density curves of single PEMFC

Polarization and power density curves of single PEMFCs with serpentine channels having rectangular and trapezoidal cross-section as shown in Fig.12. T_c: 80 ºC; T_{hc}: 80 ºC; T_{ha}: 80 ºC; O_2 pressure: 1 bar; H_2 pressure: 1 bar; PTFE content in both anode and cathode Micro Porous Layer: 15 wt%. Anode and cathode catalyst: 20 wt% Pt/C, Pt loading 0.4 mg cm^{-2}.

They concluded that the use of serpentine channels with rectangular cross-section shape was more effective when $T_{ha,c} = T_c$, while the trapezoidal cross-section shape was more suitable when $T_{ha,c} > T_c$.

III. CONCLUSION

In this paper design aspects of serpentine flow field(SFF) design such as channel height, channel width, rib to channel width ratio, channel height to width ratio, several different

SFF patterns, topology and their effect on PEM fuel cell performance is reviewed.

The flow field geometric configuration has little influence on the cell performance at high operation potentials. On the contrary, at low operation potentials, where concentration losses or mass transport are the main determining factor in PEMFC performance, geometric configuration significantly affects.

Serpentine flow fields enhance uniform reactants distribution over the catalytic layers, increasing the current density values and performance of the cell.

However, for the practical use, there should be a compromise between manufacturing cost and performance.

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