17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0438

EFECTS OF BIPOLAR PLATES DESIGNS IN THE PERFORMANCE IN PEM FUEL CELLS

A. R. Q. Panesi

Institute of Energy and Nuclear Research (IPEN-CNEN), Center of Fuel Cells and Hydrogen (CCCH), São Paulo, SP, Brazil.

Abstract *- The main objective of this article is to compare two cross-sectional shape type: trapezoidal and rectangular serpentine flow field used in PEMFCs cells, employing computational fluid dynamics (CFD) technique. The effects of different parameters on the behavior on the fuel cell that were investigated include the water concentration, pressure and velocity distribution and membrane current density. In general, the trapezoidal format, besides contributing to the accumulation of water in the channels of the cathode, also presents the tendency to an irregular pressure drop. The fuel cell with rectangular channel was equivalent to the trapezoidal cell in polarization curves. However, the current generation in the rectangular design was slightly higher. The contribution of this work is in the dissemination of the knowledge of the use of computer simulation to solve problems in PEM fuel cells.*

Keywords: *CFD, PEM fuel cell, fuel cell modelling, numerical simulation, bipolar plates*

1. INTRODUCTION

Proton exchange membrane fuel cells (PEMFC), are built out of membrane electrode assembly (MEA) which include the electrodes, electrolyte, catalyst, and gas diffusion layers (GDL) and are an interesting alternative for electrical power generation. They operate at low temperatures of about 30 to 100 °C and require catalysts to increase the rate of anode reactions. As fuel, hydrogen or liquid fuel, such as methanol or ethanol is used, and as oxidant the oxygen contained in the air. The bipolar plates have the function to distribute the reagents uniformly on the surface of the diffusion layer by means of flow channels that differ in the constitutions of the geometries implying in strong influence in the final performance of the cells. The materials used in bipolar plates are metals, graphite or carbon-based compounds. When the gaseous hydrogen is used as fuel, it is injected with a certain pressure and flows through the channels until it contacts the platinum-based catalyst at the anode, thereby suffering oxidation and releasing electrons by the following reaction:

$$2H_2 \longrightarrow 4H^+ + 4e^- \qquad (1)$$

The ion H formed by the bond breaking of the hydrogen molecule, bounds to the water molecule forming the hydroxyl ion H_3O^+, also called proton. The ions H_3O^+ are driven by the electric field generated due to the contact with the membrane structure, thus occurring the displacement of electrons through an external circuit with the emergence of a direct current. At the cathode, oxygen in the gaseous state enters the flow channels with a certain pressure and flow rate, and when the catalyst is contacted, the following reduction half-reaction occurs:

$$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O \qquad (2)$$

The product formed is water which is transported to the outlet of the bipolar plate. Bipolar plates are one of the most important components in PEMFC and must perform a number of functions simultaneously in order to achieve good stack performance and lifetime. Also, they provide structural support for the MEAs and means to facilitate water management within the cell. Geometrical designs can include straight, serpentine, interdigitated, integrated, pin-type among others found in the flow fields literature as can be seen below. Therefore, optimal design must be sought for the bipolar plates because the different functions have conflicting requirements on the design. A good design of bipolar plates must present low-cost lightweight construction materials, easy to manufacture and their positive impact on PEMFC performance. According to Paulino (2014) the study of the flow channel geometry in PEMFC with computational support provided the visualization of the results of geometrical designs in rectangular, trapezoidal and step form and with serpentine and interdigitated plates. The author concluded that the rectangular channel format presented superior electrical performance when compared to the other formats. However, the step geometry channels presented better results regarding water management. Skoda (2014) presented a study of flow fluids in the cathode channels of a PEMFC fuel cell. Experimental and numerical results were obtained with variations of working temperature and plate flow in parallel channels.

The experimental set-up was represented by a transparent cell with the objective of observing the phenomenon of flooding in cathode channels. As a result, it has been shown that the water saturation level increases with decreasing temperature and the experimental polarization and power curves for the oxygen flow rate of $60 ml min^{-1}$ and $115 ml min^{-1}$ at 25°C, indicated that performance remained unchanged for this variation of oxygen. Nannan et al. (2014) reported that there are four types of conventional flow channel bipolar plate geometries: parallel, serpentine, interdigitated, and pin type. In contrast to this typology of formats, a new format is proposed, that is, a bio-structure inspired by nature represented by the venation structure of a tree leaf. The forms of interdigitated and parallel bipolar plates were used in comparison to the new geometry. The results showed that the power density of the cell using the proposed model increased about 20 to 25% when compared to the two traditional models. Xianguo and Imram (2005) presented a review of the main formats of bipolar plates of flow channels used in PEM fuel cells. Initially it was shown that the pin type configuration of cylindrical or cubic shape provides a drop in cell performance due to uneven distribution of reagents and pressure drops. The parallel format, besides contributing to the accumulation of water in the channels of the cathode, also presents the tendency to an irregular pressure drop, presenting in general low performance of the cell. The serpentine design can be with a single or multiple flow channel, the gas pressure drop is smaller for multiple channel when compared to the single channel. Also, the authors presented the integrated format which has a cooling system along the channels thus improving a power density. Finally, the interdigitated type geometry presented a better result when removing water from the cathode side, thus avoiding the phenomenon of flooding. Freire (2013) carried out comparative studies between different cathodic flow channels using graphite plates of interdigitated and trapezoidal designs. Performance tests were compared with the conventional serpentine model. The trapezoidal model had good response to medium currents due to the better efficiency in the water removal present at the cathode. Peng et al. (2013) showed the flow channels of a PEM type fuel cell inspired by nature in fractal forms and biological sources. The authors comment that the rules of channel design should provide efficient water removal, facilitate electron transport, promote a better distribution between the reactant gases, also minimize the gas pressure drop between the inlet and outlet of the channels and finally should be easy to manufacture. Through a computer simulation, a working cell at 80°C using hydrogen and air with parallel and nature-inspired channels designs was compared. According to the results, the current density for the proposed model presented values slightly higher. Manso et al. (2012) showed the influence of the geometric parameters of the flow channels on the performance of PEM type fuel cells. For low power density, the influence of geometries on cell performance is significantly affected. The authors agree that the serpentine and interdigitated designs also help the elimination of the condensed water at the cathode as well as promote a better uniformity in the distribution of the reactants. The narrower cross-section of the channel produces better results in the serpentine configuration, while reducing the depth of the channels especially on the side of the cathode, improves mass transfer, aiding in the elimination of water. This variation of channel height only has effects when the cell operates with low work potentials. Rahimi-Esbo et al. (2016) simulated seven different 100 cm^2 flow-field patterns the CFD process, where they are 1-channel serpentine, 2-channel serpentine, 3-channel serpentine, 2-1-channel serpentine (two channel serpentine at the beginning converted to one channel at the end), 3-2-channel serpentine, 4-3-channel serpentine and 5-4- channel serpentine. All the flow-field patterns were simulated with 0.4 V and the results showed that the serpentine model with two inputs and one output was the one that presented the highest performance especially at high current densities. Also for voltages above 0.5V, the geometry of the flow channels has no significant effect on performance. Liu et al. (2014) developed an experimental study of the use of various plate formats for flow channels in PEM fuel cells. The formats used were serpentine, parallel, interdigitated, pin type and spiral. According to the results regarding current density and power density, the serpentine configuration was the one with the highest values followed by the parallel configuration of pin type, interdigitated and finally in a spiral. The authors reported that the serpentine configuration presented the best results both in the removal of water and in the values of current and power density. Lim et al. (2016) presented a literature review on the influence of flow channel geometry on water management and reagent distribution in PEM fuel cells. The authors comment that the parallel configuration is the simplest of all and it induces pressure drop during the gas flow due to high flow rates, as the flow decreases, the pressure drop decreases, but on the other hand impairs the removal of water from the cathode. The serpentine format contributes to improve the uniformity of the reactant gases as well as the removal of water, but, it presents a greater drop of pressure when compared to the format in parallel. The interdigitated form has non-continuous and no-out channels that improve convection flow improving water removal. Also, the authors argue that the parallel format is best suited for automotive applications because of the simple design that reduces manufacturing costs. Wang et al. (2007) performed simulation studies on bipolar plates with parallel and interdigitated channel format. The models were used to investigate the effects of the flow channel area ratio and the cathode flow rate on the cell performance and local transport characteristics. For the parallel flow channel design, as the flow channel area ratio increases the cell performance improves because fuel is transported into the diffusion layer and the catalyst layer mainly by diffusion, while the interdigitated flow channel design, the baffle forces more fuel to enter the cell and participate in the electrochemical reaction, so the flow channel area ratio has less effect compared to parallel format. Paulino et al. (2017) compared numerically and experimentally the influence of the flow channel cross-section in the water distribution inside the cell, studying rectangular, trapezoidal and hybrid stepped geometries. The results of this numerical simulation showed that the fuel cell with stepped channel was equivalent to the trapezoidal cell in all aspects analyzed, and both provided superior water management than the rectangular cell. However, the current generation in the rectangular design was slightly higher. Choi et al. (2011) studied the influence of different channel heights and widths on the performance of a PEMFC. The obtained results showed that as the channel height increases, the pressure drop is decreased because of the increase in cross-sectional area of the gas flow. This effect caused accumulation of liquid water at the outlet, slightly reducing the cell performance. Besides that, as the channel width increases, the cell voltage decreases in large value. Scholta et al. (2006) investigated the influence of channel geometry on performance using a parallel based flow field using a computational fluid dynamics program (CFD). As a result, smaller channel dimensions were preferable for high current densities, whereas wider dimensions were better at low current densities.

2. COMPUTATIONAL FLUID DYNAMICS MODELLING OF FLOW FIELDS

Using computational fluid dynamics (CFD) software, it is possible to save some time and expense involved in testing fuel cell designs. For this analysis, modeling and simulation were executed in the commercial software COMSOL Multiphysics 5.2a, which was used to build a single-phase isothermal and tridimensional fuel cell model with finite element method. For this model, the following conditions were assumed: isotropic and homogeneous membrane and electrode structures, isothermal system, ideal gas mixtures, incompressible and laminar flow. Two designs were selected for investigation: trapezoidal and rectangular serpentine flow field bipolar plates. This model investigates the steady-state transport of reactants and water in a cell including both anode and cathode mass and momentum transport phenomena in the flow channels, gas diffusion layers and porous electrodes, as well as electrochemical currents in the GDLs, the porous electrodes and the polymer membrane. Water production on the cathode side was also investigated. The principle of simulation was based in the coupling in two reacting flow in porous media, concentrated species interfaces to one secondary current distribution interface. In addition, special equations are apply in fuel cell such as:

- Darcy's equation for fluid flow in porous media,
- Stefan-Maxwell equation for multispecies diffusion,
- Faraday Law in electrical current and electrochemical reaction,
- Butler-Volmer equation between electrical current and potential,
- Ohm's law of electrical current conduction.

Besides that, the conservation equations are also used in general be represented by the solution of conservation for mass, momentum, energy, species and current transport. This way, the current potential relationship with the Butler-Volmer equation is determined by:

$$i = i_0 \left\{ exp\left[\frac{-\alpha_{Rd} F(E-E_r)}{RT}\right] - exp\left[\frac{\alpha_{Ox} F(E-E_r)}{RT}\right]\right\} \quad (3)$$

This model investigates the steady-state transport of reactants and water in a cell including both anode and cathode mass and momentum transport phenomena in flow channel cross section, gas diffusion layers and porous electrodes, as well as electrochemical currents in the GDLs, the porous electrodes and the polymer membrane.

3. GEOMETRICAL CHARACTERIZATION

In this study, all geometric models were built based on the bipolar plates of a sixteen channels serpentine fuel cell of 25 cm^2. Figure 1 shows the dimensions of the cross sections for the two main geometries.

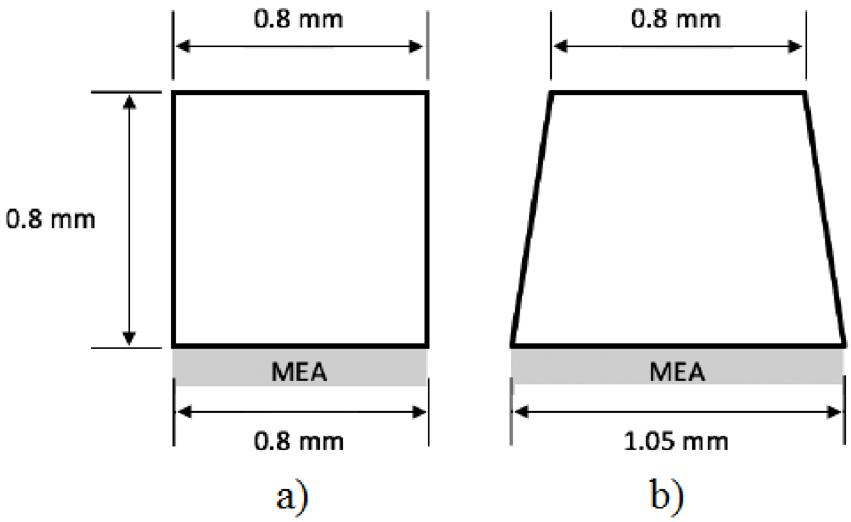


Figure 1. Geometrical characterization of flow- fields: a) rectangular, b) trapezoidal

The rectangular and trapezoidal section channel are widely used in experiments, including experiments conducted at the IPEN laboratories. The advantage of trapezoidal section is to provide a larger contact area between the MEA and the channel, facilitating the diffusion of reactants and products by causing minor potential losses of mass transport.

4. NUMERICAL SIMULATION

The mathematical models that describe the electrochemical reactions in fuel cells is Butler-Volmer equation, which was applied in the present work. Model parameters and operation conditions are given in tables 1 and 2, respectively. The water concentration, pressure distribution, velocity distribution and membrane current density for different bipolar plates geometry were compared using this simulation model as well as the performance of the PEMFC.

Table 1. Geometric parameters used in the simulation model

	Bipolar plate geometry	
	trapezoidal	rectangular
Channel length (mm)	22.55	22.55
Channel width (mm)	0.8	0.8
Channel depth (mm)	0.8	0.8
Rib width (mm)	0.65	0.65
Membrane thickness (µm)	0.184	0.184
GDL thickness (µm)	0.200	0.200
Catalyst layer thickness (µm)	0.150	0.150
Flow rate anode (mlmin^{-1})	300	300
Flow rate cathode (mlmin^{-1})	200	200
Temperature operation (°C)	80	80

Table 2. Operation conditions used in the simulation model

Parameters	Value
GDL porosity	0.4
GDL permeability	1x10^{-12} m^2
GDL electric conductivity	1000 S/m
Inlet H_2 mass fraction (anode)	0.6
Inlet H_2O mass fraction (cathode)	0.023
Inlet oxygen mass fraction (cathode)	0.6
Anode viscosity	1.19x10^{-5}Pa.s
Cathode viscosity	2.46x10^{-5}Pa.s
Hydrogen molar mass	0.002kg/mol
Water molar mass	0.018kg/mol
Oxygen molar mass	0.032kg/mol
Reference pressure	101.325Pa
Cell voltage	0.4-0.9V
Oxygen reference concentration	40.88mol/m^3
Hydrogen reference concentration	40.88mol/m^3
Electrolyte phase volume fraction	0.3
Open volume fraction for gas diffusion in porous electrodes	0.3
Permeability (porous electrode)	2x10^{-13} m^2
Membrane conductivity	14S/m

5. RESULTS AND DISCUSSIONS

5.1 Pressure distribution

A high pressure drop can cause many problems, for example, the high parasite power, pressure gradient between the adjacent channel and finally cause serious mechanical stresses between inlet and outlet. Everything contribute to low efficiency of the fuel cell. Figure 2 shows the pressure (Pa) in both types of channel geometry in cathode side.

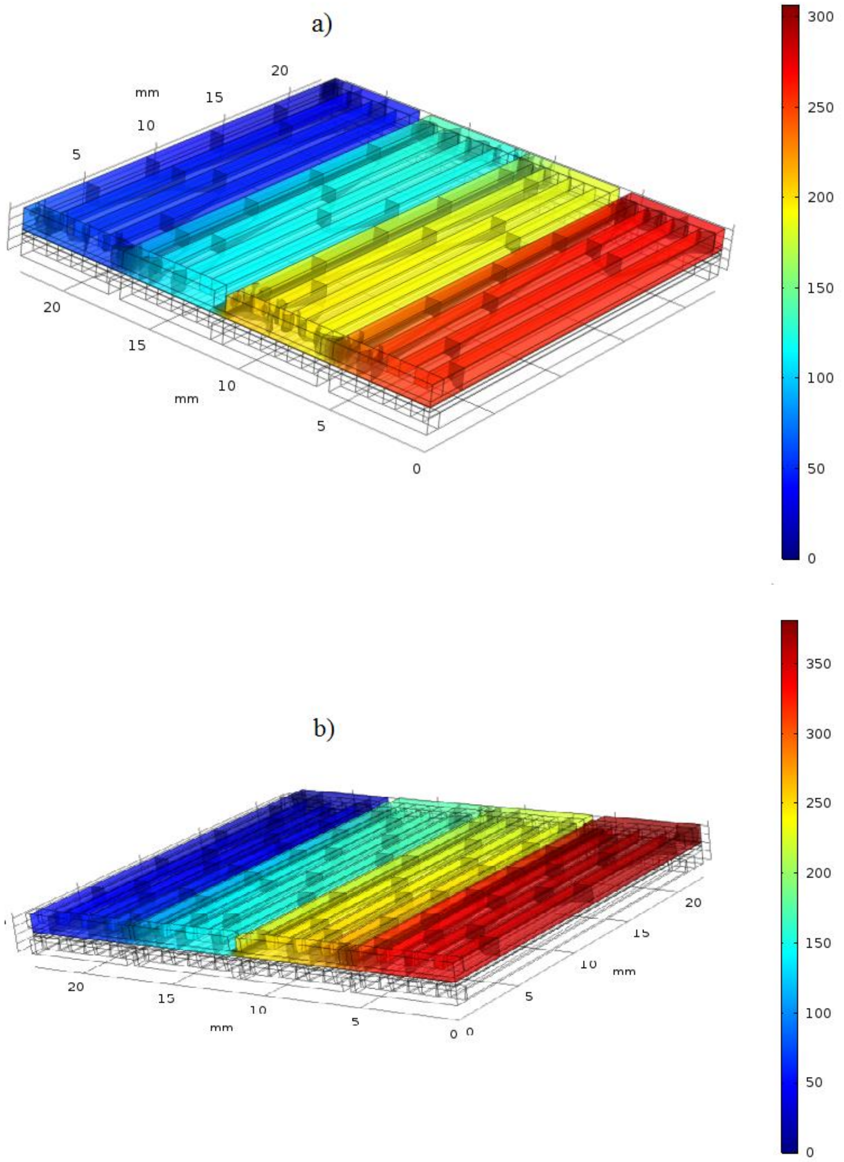


Figure 2. Pressure distribution (a) rectangular (b) trapezoidal

According to the Figure 2 there is a significant pressure difference between the upgoing and downgoing parts of the channel in both types of channel geometry.

5.2 Water concentration

In general, fuel cells operate in different situations, such as: configuration of channels, gases flow rate and surfaces with different GDL, making it difficult to identify the flow patterns of the channels. The optimization of water management, has a great influence on the fuel cell, where the mass fraction of water produced at the cathode cannot accumulate on the catalyst. In the present study, water was studied between different channel designs and the concentrations of water (%), the water produced in the cell is assumed to be water vapor and there is no condensation or evaporation.

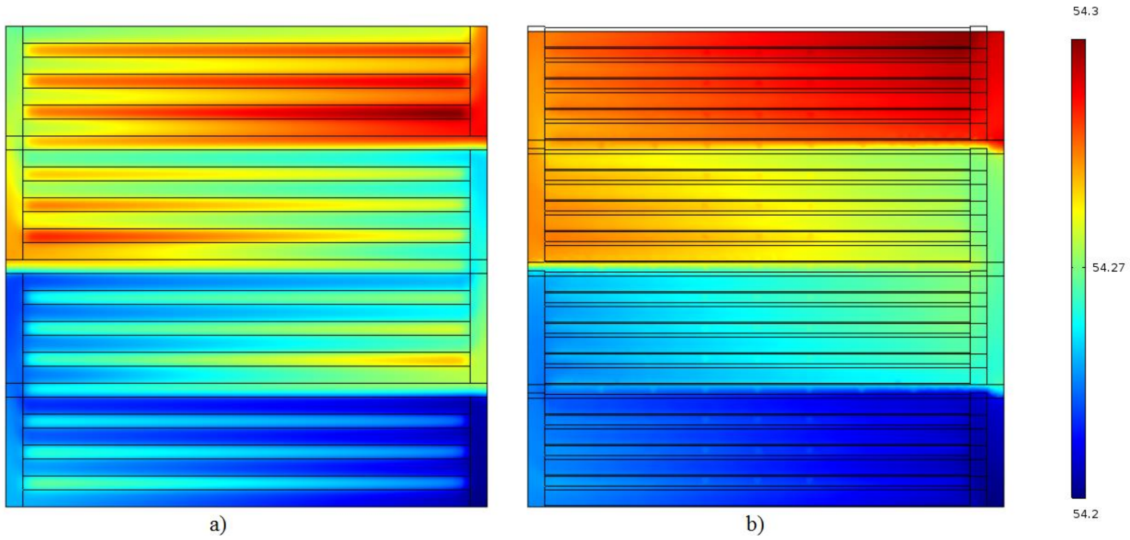


Figure 3. Molar fraction of water (a) rectangular (b) trapezoidal

It is very essential to know the water transport along the cathode channel since the water concentration is closely associated with the ionic conductivity of the membrane. In Figure 3 show the water distribution at the fully humidified cathode side. The mass fraction of water content gradually increases from the inlet to outlet, showing that formation is increased due to the electrochemical reaction, but also of proton transporting simultaneously through the membrane from anode side, known as by electro osmotic drag. The mass fraction of water for the rectangular geometry is practically similar to the geometry trapezoidal, but the trapezoidal showed superior concentration on the channels output (upper side of the Figure 3).

5.3 Velocity distribution

In Figure 4, velocity distribution contour in the flow field of the cathode channel is shown. The rectangular format show slightly higher velocity contributing this way, with water management avoiding the accumulation of water in the porous layers as shown in the Figure 3.

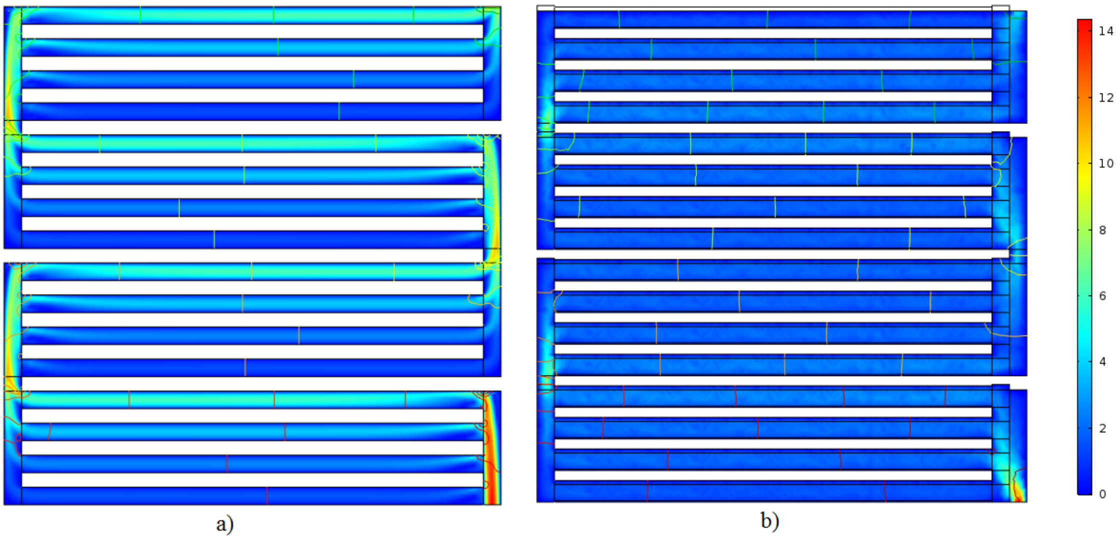


Figure 4. Velocity in the cathode **(a)** rectangular **(b)** trapezoidal

5.4 Membrane current density

Figure 5 shows the distribution of current in the membrane. In the rectangular geometry the current distribution is more uniform, while in the trapezoidal plate the current is distributed more in the central region of the cell.

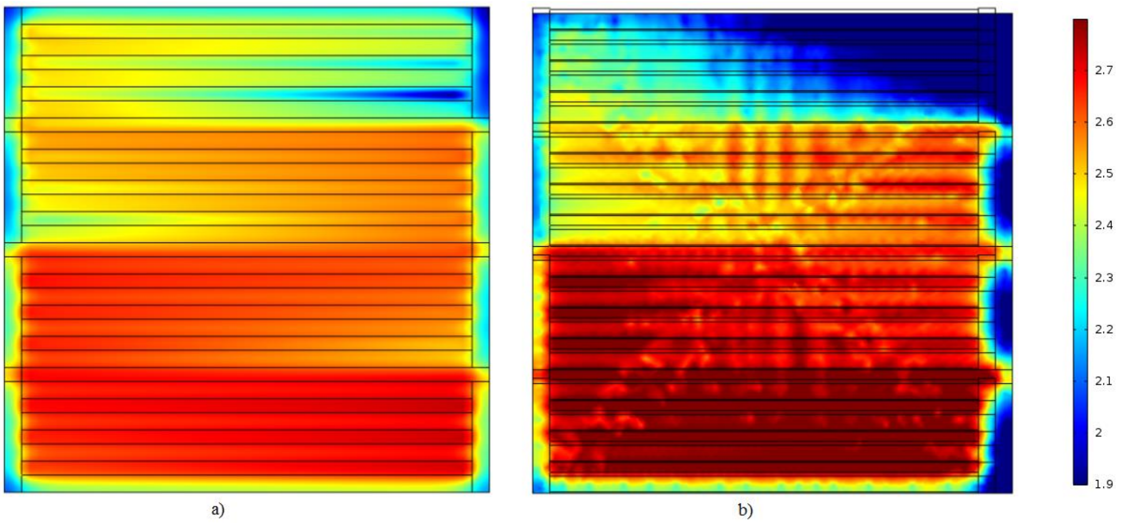
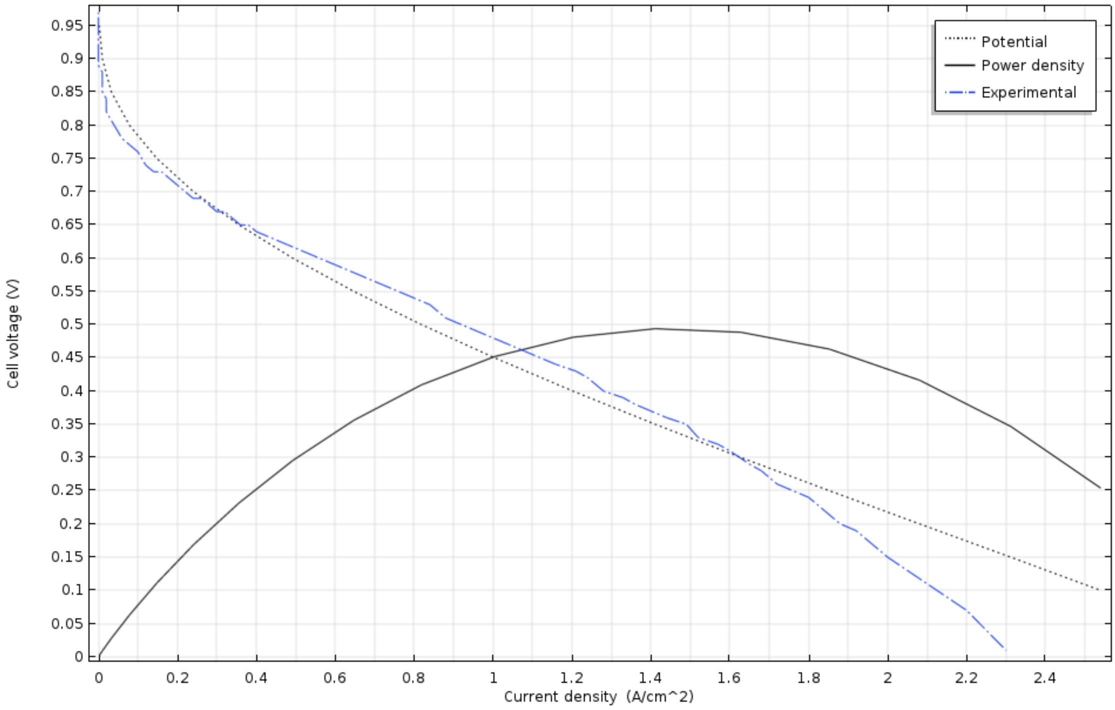


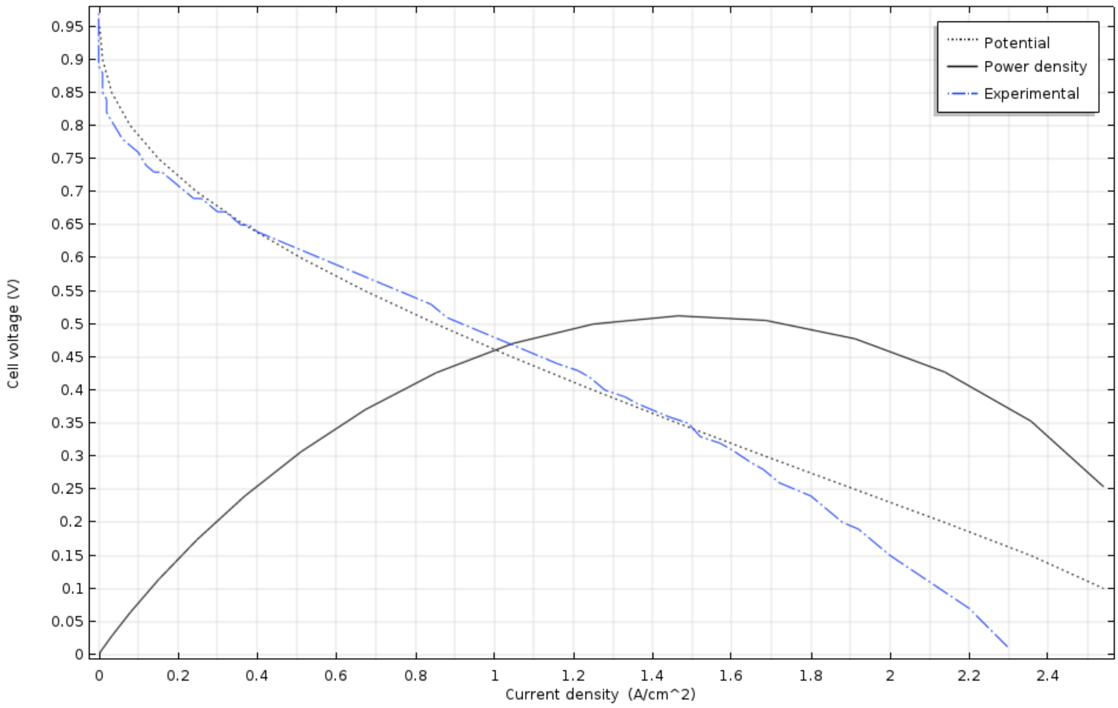
Figure 5. Membrane current density **(a)** rectangular **(b)** trapezoidal

5.5 Polarization curves

As can be seen in Figure 6, the comparison of numerical and experimental polarization curves using different flow field designs. According the Figure 6, the performance is not significantly affected by pattern design. The difference between numerical and experimental results was less than 10% for most of the current densities in the designs, indicating that the simulation was able to accurately model fuel cells.



a)



b)

Figure 6. Comparison of numerical and experimental results using different flow field designs **(a)** rectangular **(b)** trapezoidal

6. ACKNOWLEDEGEMENTS

The author acknowledge the support of Institute of Energy and Nuclear Research (IPEN-CNEN), Center of Fuel Cells and Hydrogen (CCCH).

7. REFERENCES

Arvay, A., French, J., Wang, J. C., Peng, X. H., Kannan, A. M. Nature inspired flow field designs for próton Exchange membrane fuel cell. Int. J. Hidrogen Energy, v. 38, pp. 3717-3726, 2013.

Choi Kap-Seung, Kim Hyung-Man, Moon Sung-Mo. Numerical studies on the geometrical characterization of serpentine flow-field for efficient PEMFC. International Journal of Hydrogen Energy 2011, 36: 1613-27.

Freire, L. S. *Estudo da influência dos parâmetros operacionais de células a combustível do tipo PEM utilizando geometria dos canais de distribuição dos gases diferentes no eletrodo catódico*. Dissertação de Mestrado, UFAM, Manaus, 2013.

Hong Liu, Peiwen LI, Daniel Juarez Robles, Kai Wang, Abel Hernandez Guerrero. Experimental study and comparison of various designs of gas flow fields to PEM fuel cells and cell stack performance. Energy Research, v. 2, pp. 1-8, 2014.

Lim, B. H., Majlan, E. H., Daud, W.R.W., Husaini, T., Rosli, M. I. Effects of flow field design on water management and reactant distribution in PEMFC: a review. International Journal of Ionics the Science and Technology of Ionic Motion, v. 22, pp. 301-316, 2016.

Manso, A. P., Marzo, F.F., Barranco, J., Garikano, X., Mujika, M. G. Influence of geometric parameters of the flow fields on the performance of a PEM fuel cell. A review. Int. J. Hidrogen Energy, v. 37, pp. 15256-15287, 2012.

Nannan, G.; Ming, C. Leu.; Umit, O. Koylu. Bio inspired flow field designs for polymer electrolyte membrane fuel cells. Int. J. Hidrogen Energy, v. 39, pp. 21185-21195, 2014.

Paulino, A. L. R. *Estudo da geometria de canais de fluxo em células a combustível tipo PEMFC utilizando fluidodinamica computacional.* Disertação de Mestrado, IPEN. São Paulo, 2014.

Paulino, A. R. L., Cunha, E. F., Robalinho, E., Linardi, M., Korkischko, I., Santiago E. I. CFD Analysis of PEMFC Flow Channel Cross Sections. Fuel Cells, v. 1, pp. 27-36, 2017.

Rahimi-Esbo, M., Ranjbar, A. A., Ramiar, A., Alizadeh, E., Aghaee, M. Improving PEM fuel cell performance and effective water removal by using a novel gas flow field. Int. J. Hidrogen Energy, v. 41, pp. 3023-3037, 2016.

Scholta, J., Escher, G., Zhang, W., Kuppers, L., Jorissen, L., Lehnert, W. Investigation on the influence of channel geometries on PEMFC performance. J. Power Sources 2006, 155- 66.

Skoda, S. *Hidrodinâmica do escoamento dos canais catódicos de uma célula a combustível de membrana polimérica condutora de prótons*. Tese de Doutorado, IPEN, São Paulo, 2014.

Xianguo, Li.; Imran, Ssbir. Review of bipolar plates in PEM fuel cells: flow-field designs. Int. J**.** Hidrogen Energy, v. 30, pp. 359-371, 2005.

Xiao-Dong Wang, Yuan-Yaun Duan, Wei-Mon Yan. Numerical study of cell performance and local transport phenomena in PEM fuel cells with various flow channel área ratios. Journal of Power Sources, v. 172, pp. 265-277, 2007.

8. RESPONSIBILITY NOTICE