

## **Study of the Flow Fluids and Design Engineering Under PEM Fuel Cell Working Conditions**

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This document presents a study of the design and functionality characterization of current, voltage and power for a PEMFC (Proton Exchange Membrane Fuel Cell). Design Engineering is applied to manufacture current collector plates (polar plates), particularly for feeding reaction gases and to the type of feeding. Its purpose is to understand the effect of fluid flow phenomena of reagent gases on the PEMFC, using high purity hydrogen and oxygen. The PEMFC performance study was done by obtaining polarization curves at room temperature, applying a two factor (pressure and flow type) experimental design with different pressure levels for each factor. This experimental design applies four different pressure levels inside the cathodic compartment and two flow types for feeding the reagent gases: the co-current and crosscurrent flows. Results show a positive effect on the performance of the PEMFC due to the two experimental factors. Greater current densities are obtained when PEMFC is working with crosscurrent flow, whereas greater electrical power levels are observed in the co-current flow.

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**Keywords:** Fuel cell, design engineering, feeding flow, PEMFC functionality

### **1. INTRODUCTION**

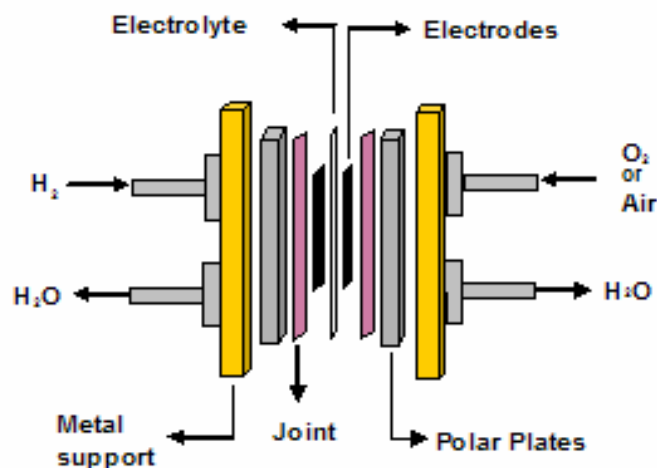
Industrial and commercial human activities have produced environmental problems such as atmospheric global warming, linked to the combustion of fossil fuels. Nevertheless, at the beginning of the third millennium, Fuel Cells (FC) have proven to be an efficient environmental technology for energy generation [1]. Nowadays there are six different FC technologies available: Phosphoric Acid

FC, Proton Exchange Membrane FC, Alkaline FC Molten Carbonate FC, Solid Oxide FC, Direct Methanol –Air FC [2].

In particular, PEMFC offers many technological advantages such as: greater fuel efficiency, high stability, high oxygen solubility and high mechanical strength. The technology could also be applied to electric vehicles [2-4]. PEMFC technology has been applied to vehicles for air, sea (submarines) and land transport, but it is not limited only to them; other stationary and portable applications have been developed. [5-10].

The scientific basis for this technology was developed in 1802, when Henry David announced the reverse electrolysis principle; his work provided the evidence for producing electricity from the chemical reaction between oxygen and hydrogen. The FC principle was published by Christian Friedrich Schönbein in the philosophic magazine in January 1839, but the first Hydrogen-Oxygen FC was made in 1839 by Sir William Robert Grove, known as “the father of fuel cells”. Grove obtained electricity, heat and water as products, so he published those results in the same magazine and the same year as Schönbein. Grove’s FC was made of platinum and zinc, with electrodes with oxygen and hydrogen closed tubes and nitric acid as the electrolyte. In the 1960’s NASA renewed its efforts to use FC in their space projects, including Apollo, Gemini and Spacelab [1, 3, 11]. Since 1970’s many research groups around the world have been developing new FC technologies with new materials, design engineering and optimization for reducing the FC cost in order to implement energy diversification and environmental programs.

A FC as PEMFC is an electro-chemical device that converts chemical energy due to reverse hydrolysis into electric energy; water and heat are residual reaction products, but a good weight/power ratio is obtained [5-7]. PEMFC are also called SPFC (Solid Polymer Fuel Cell) [1-3,1 2] and operate up to 120°C with a pressure of 1 to 5 atmospheres. A typical PEMFC monocell is constituted of an anodic electrode, a cathodic electrode and a hydrated polymeric electrolyte commonly made of Nafion®. These elements are assembled in the Electrode-Membrane-Electrode (EME) order, and they are located between two polar plates commonly made of graphite, which are supported by two polar plates, copper for instance. Figure 1 shows the scheme of an open monocell PEMFC.



**Figure 1.** Schematic of PEM Fuel cell

Nowadays, PEMFC technology research and development have made advances on three of the main elements presented in figure 1: a) porous electrodes (electrocatalysis), b) protons conductive membrane and c) current collector plates [3-4, 8]. The membrane is sandwiched between two platinum catalyzed porous electrodes in a PEMFC, but better results have been reported when using Ru and Ru-PT alloys [9]. On the other hand, the polymeric membrane electrolyte is a perfluorosulfonic type, known commercially as Nafion<sup>®</sup> and developed by Du Pont de Nemours<sup>®</sup>.

These membranes have three types: Nafion 112 (50  $\mu\text{m}$ ), Nafion 115 (100  $\mu\text{m}$ ) and nafion 117 (120  $\mu\text{m}$ ), all values given in dry condition [3]. Some recent studies related to Nafion membranes doped with metals have shown an increase in ionic transport. Also polysulfonic membranes appear to be an important alternative for their application in PEMFC technologies [8, 16]. It is important to mention that other components such as gas conductors and current collectors were made over graphite plates or stainless steel [17].

Polar plates, collector plates and gas conductors have three functions. First: to give a homogeneous distribution of reactive gases over the porous surfaces of electrodes. Second: to collect the generated current on all the points of reaction in the anode, while for the cathode surface electric current and its distribution is considered. The third function is to support the EME assembly [12-13, 18]. The main characteristics of support plates are the capacity to support the fuel cell, to allow gases to feed, and to facilitate the control of cell temperature. This article presents the study of design engineering, building and characterization of a PEMFC. The designs of polar plates and support plates are shown, in addition to polarization curves in order to determine the PEMFC performance at different cathodic pressures and types of flow in the system, co-current and counter current.

## 2. DESIGN CONDITIONS

### 2.1. Polar plates

In order to have a complete monocoil, the assembly of the polar plates upon the EME structure should be done, but it is a necessity that enough force and packing be applied to this assembly to avoid the escape of reactive gases in order to obtain a good electric contact. At this point, assembly is a very critical task, because for instance, graphite polar plates could be broken, but given that borders are a critical zone, it is a necessity to use a mechanical support. EME assembly is generated by thermo pressure [3, 16, 18], a minimum contact between carbon electrodes; catalyst and electrolyte are needed. The resultant assembly generates active zones where half-reactions in electrodes are presented, so this is called the "Triple Contact Zone".

Some authors have reported metal or non porous graphite as polar plates materials, but having the following characteristics: enough electric conductivity, physical support for assembly forces and providing gas transport inside the cell through a correct channels design [3, 8, 17, 19]. In this work we have chosen nuclear grade graphite due to malleability and cost.

Due to the problem of water accumulation as a by-product, a good geometric design is needed for water drainage, so there are many designs and schemes for this purpose [17, 19]. In this work, the proposal design is one of a channel in a coil shape as in figure 2, where the input and output of the

system are on the same plate side and the respective used area is  $9 \text{ cm}^2$ . This design allows: 1) a continuous flow in order to avoid water accumulation 2) the flow of the reagents on the active layer, therefore eliminating the problem of areas with suspended flow. On the other hand, geometric configuration at the incoming of distribution channels modifies the speed profiles when diameter reductions on conduits are applied. Then, if a sudden change in diameter occurs, a loss of mechanic energy could happen in the flow [20] at the input of the distribution channel on the polar plates. Also,

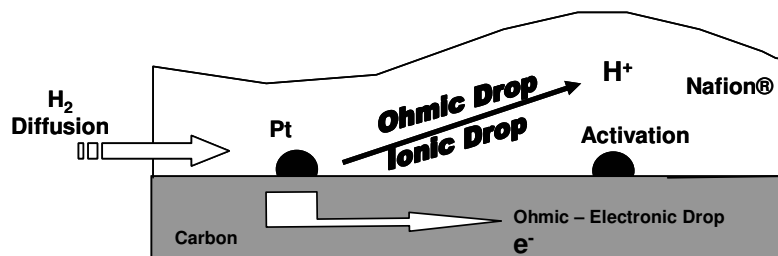


Figure 2. Schematic of the triple contact zone: Carbon-Catalyst-Electrolyte

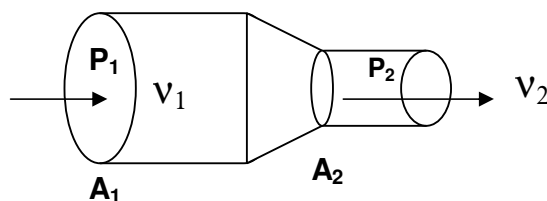


Figure 3. Schematic of the Venturi pipe

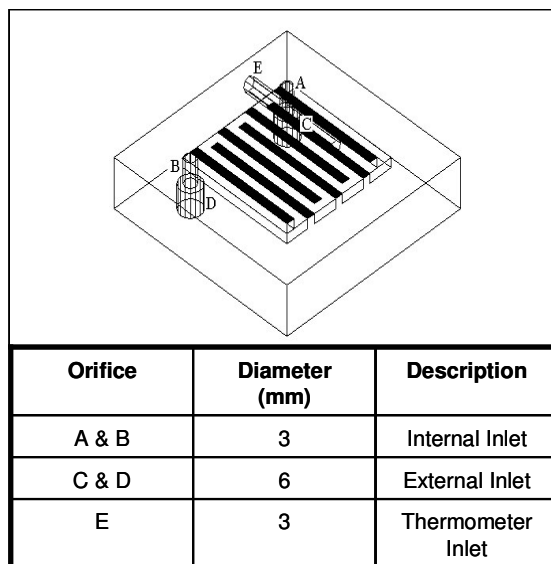


Figure 4. Schematic of the Polar Plates

suspended flow can appear when coming out of the distribution channels due to the effect of the sudden change of diameter in the conduits. In order to avoid these inconvenient phenomena in the flow

of the reagents, we propose a well-known geometric configuration like Venturi, as shown in figure 3, where the inlet diameter is greater than the exit diameter for improving the flow profiles and their speed during the conduction and distribution of gases on the porous electrodes in the PEMFC.

Where  $P_1$  and  $P_2$  are the input and output pressure respectively,  $A_1$  and  $A_2$  are the transversal areas for flow of fluid,  $V_1$  y  $V_2$  represents the flow speed at the input and output respectively. In this array  $P_1 > P_2$  due to  $V_1 < V_2$ . So the output speed from the Venturi's tube is given by equation 1 in units of the International System [20], where  $\rho$  represents the flow density in the transport. The proposed design of polar plates is presented in figure 4.

$$V_2 = [((P_1 - P_2) * 2) / (\rho * (1 - (A_2/A_1)^2))]^{1/2} \dots\dots (1)$$

### 2.2. Support plates

Support plates are made of metal due to their mechanical resistance and electric conductivity. In this work, cooper plates have been selected due to their low electrical resistance and low cost. Design conditions for this supports are: 1) union supports between anode and cathode for an effective and efficient assembly, 2) two connections per plate that allows the input of gases to the polar plates and output of residual gases, 3) An orifice threaded in the cross sectional side of each copper plate (external circuit terminals on their respective transversal faces) will allow for the external electric circuit connection for the electric current conduction produced by the semi reaction, as shown in figure 5.

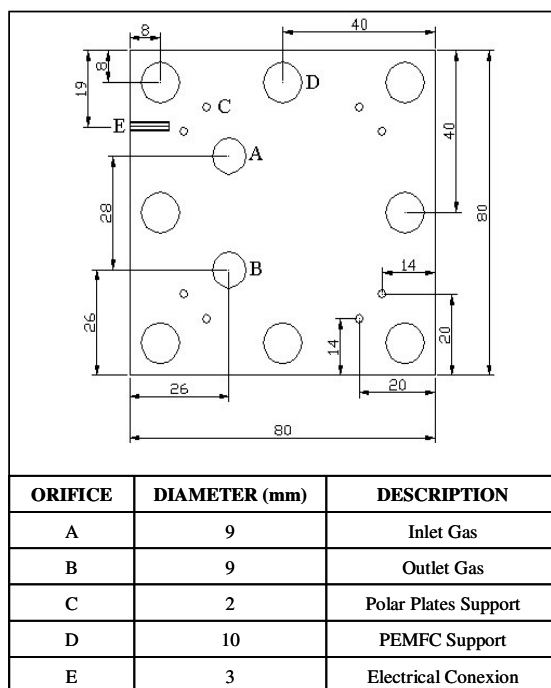


Figure 5. Schematic of support plates

Our completely assembled PEMFC is shown in figure 6, where two copper plates support the EME assembly and the graphite plates. Also eight aluminum rods surround the polar plates, serving as

guides to avoid rods from being outside of the center during the joint. Rods are retired at the end of the assembly process to avoid a short circuit. A hermetic pressure of 4 N\*m is applied on the assembly by means of eight screws covered with termofilm for electrical securing; in addition screws have metallic earring and insulator earring.



**Figure 6.** PEMFC designed picture.

### 3. EXPERIMENTAL PART

The EME assembly of the designed PEMFC takes into consideration that commercial electrodes (E-tek) and their main components are a carbon fabric that provides support, mechanical resistance and low losing electrical conductivity. This fabric is impregnated with an agglomerate of platinum supported on vulcan type carbon and a Nafion® film equivalent to 0.7 mg/cm<sup>2</sup> [17,21-22], their thickness and weight are 0.35 mm and 116 g/m<sup>2</sup> respectively. These electrodes have a Pt catalyst

**Table 1.** Experimental design for the operational conditions in the PEMFC.

Variables (units)	Anode	Cathode
Gas flow (cc/min)	50	50
Presion (psi)	4	4,6,10 y 14
Humidify Temperature (°C)	35	35
Cell Temperature (°C)	Ambiental	Ambiental

load at 20 % weighth / C of 0.4 mg/cm<sup>2</sup>. Also the load of Nafion and catalyst are only present on the active face, which means the face in contact with the electrolyte, as much for the cathode as for the anode. A 2 cm<sup>2</sup> membrane made of Nafion® 115 of 100 µm thickness was used and it has a tick of 120µm after activation as previously reported. [3,16, 18-22]. On the other hand the used electrolyte is equivalent to 25 cm<sup>2</sup> (5 x 5 cm), and the combustible gas fed to the PEMFC was of high purity (H<sub>2</sub>, UPC Grade at 99.9993% Infra) as well as the oxidant (O<sub>2</sub>, ZERO/UHP Grade at 99.8 % Infra). The

experimental design for this study involves two factors: type of flow and pressure inside the cathodic compartment. Co-current and counter current were considered along with the two levels for flow, as well as four levels of cathodic pressure: 4, 6, 10 and 14 psi. The experimental conditions applied to our PEMFC are shown in Table 1.

Cell assembly and necessary connections in the test Branch of type “Fuel Cell Test System Globe Tech Compu-Cell GT-890-B” for characterization are shown in Figure 7

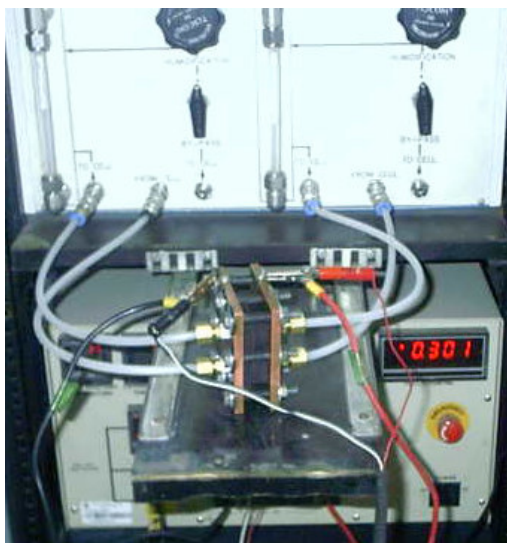


Figure 7. PEMFC mounted in the test bench

#### 4. RESULTS AND DISCUSSION

Figure 8 shows a comparison on a performance curve and developed power as a kind of feed flow reagent gases in the PEMFC. Figure 8a corresponds to co-current level and figure 8b to crosscurrent level. For both levels a 14 psi inside the cathodic compartment and 4 psi for anodic pressure were fixed for the entire experimental event.

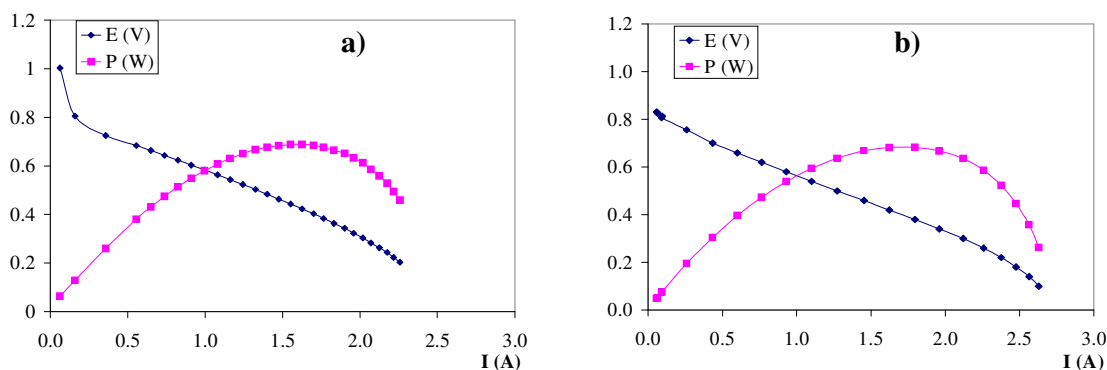
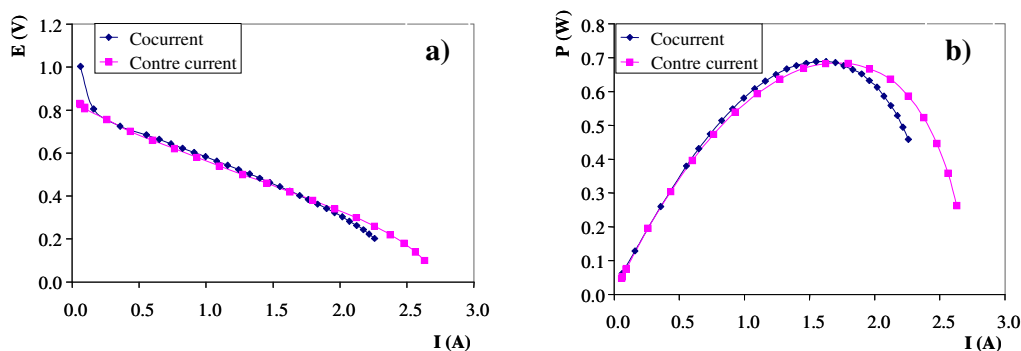


Figure 8. Performance (♦) and Power (■) curves (same scale) for the PEMFC in operation a (a) co-current flow and (b) contre current flow and 14 psi of cathode presion.

Figure 8a corresponds to results obtained for a co-current flow, where a maximum in the power curve is observed around 1.5A, and the maximum current intensity developed by PEMFC is 2.25 A at the aforementioned conditions. Figure 8b shows the cell functionality for crosscurrent flow, where the maximum of power is at 1.7A and the maximum current intensity is at greater values than 2.5 A

Similar results have been reported by Kim and team. [23], who present performance curves for a PEMFC  $H_2 - O_2$  at 1 atm (14.22 Psi) pressure in both compartments for reagent gases and at 50°C of applied temperature, but electrodes made by those authors have a load of Pt equivalent to  $0.4 \text{ mg/cm}^2$  and a load of Nafion<sup>®</sup> film of  $0.6 \text{ mg/cm}^2$ . Also, the electrolyte used was the Nafion 115<sup>®</sup> membrane. They report current densities  $0.5 \text{ A/cm}^2$  at 0.6 V and  $1.25 \text{ A/cm}^2$  at 0.1 V in their polarization curves. So Kim's team's results are similar to our work for the co-current flow case ( $1.22 \text{ A/cm}^2$  approx.) but at room temperature; nevertheless we obtain a greater current density ( $1.35 \text{ A/cm}^2$ ) than Kim's team for a crosscurrent flow considering a 30°C difference at the PEMFC temperature operation.

We consider that Venturi's design for input and output of gases contributes to a better speed and flow profile inside of the distribution channels of reagent gases located inside polar plates. This has a better effect on the performance of the PEMFC.



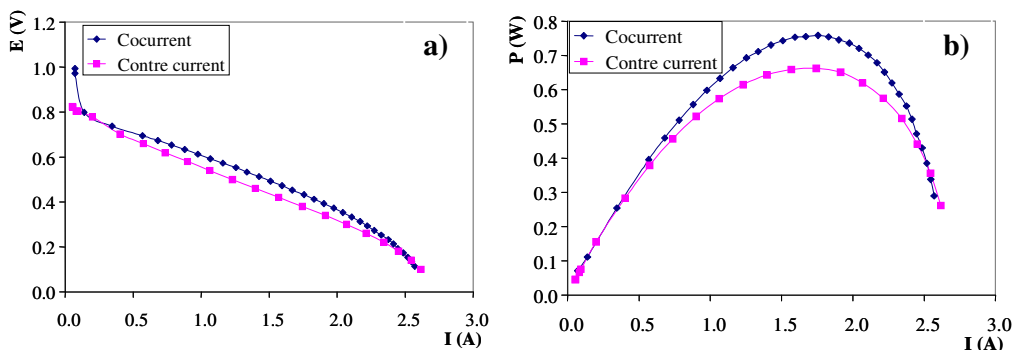
**Figure 9.** Performance (a) and Power (b) curves for the PEMFC in operation at (◆) co-current flow, (■) contre current flow and 14 psi of cathode presion.

In Figure 9a, E-I curves can be observed for both types of feeding flow at 14 psi pressure applied on the cathodic compartment. Figure shows a zone of ohmic loss between 0 and 0.35A, but a faster activation is observed for a crosscurrent flow. The zone of ohmic loss is located near to 0.35 and 2 A and they are very similar in shape. After these values there is a zone of diffusion loss, where there is a greater loss due to diffusion with the feeding reagents in the co-current flow. On the other hand, figure 7b shows the same power level (0.69 W) for both flow types but an offset is presented at greater values of current intensity.

Figure 10a shows polarization curves for the PEMFC for both flow types at 10 psi cathodic pressure where the zone of activation losses are presented. Also, an offset of current to smallest values than 0.2A are presented at the activation zone for co-current flow, although an easier activation is presented at the counter current flow; in this case, the zone of ohmic loss is around 0.2 and 2.4A, showing greater loss in counter current flow. Further, loss in the zone of diffusion is located at 2.6A, very similar for both flow types, in contrast it is shown that at lower voltages, greater current densities

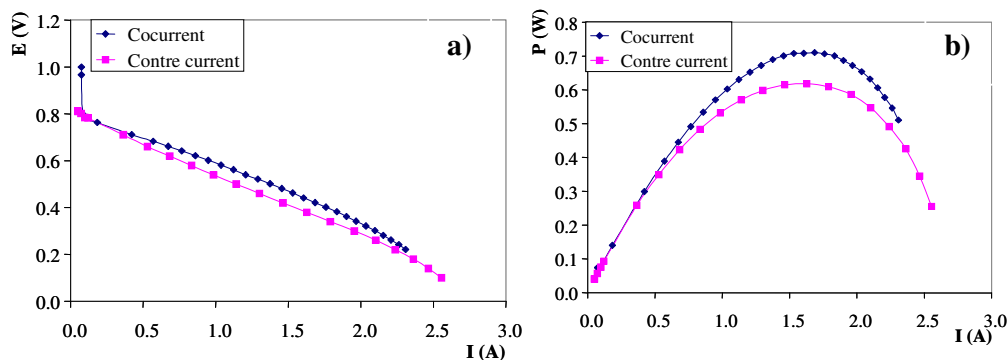


could be presented at crosscurrent flow. On the other hand, power curves shown in figure 10b show an advantage of co-current flow (0.76 W) over the crosscurrent flow (0.65 W)



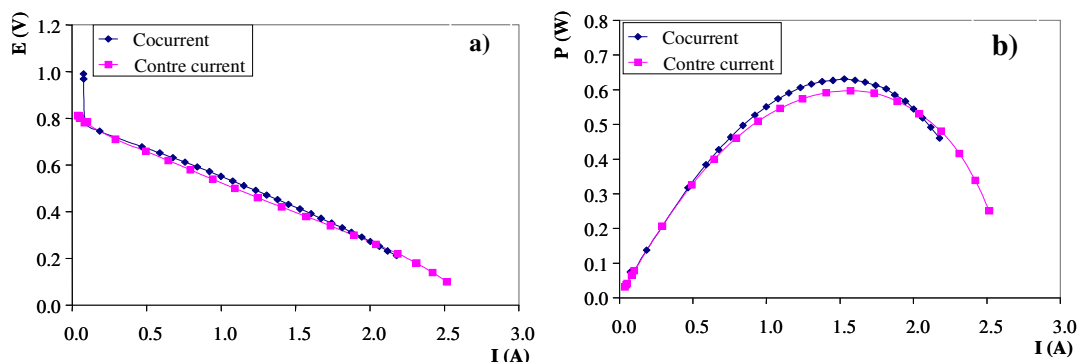
**Figure 10.** Performance (a) and Power (b) curves for the PEMFC in operation a (♦) co-current flow, (■) contre current flow and 10 psi of cathode presion.

Figure 11 shows results obtained for both types of feeding flow but at a cathodic pressure of 6 psi. Figure 11a shows that zone of activation loss is around 0.18A; in this case the counter current flow shows an activation at smaller curen values and the zone of ohmic loss is shown at 0.18A and 2.3A. Meanwhile, the co-current flow characterization shows an aparent greater diffusion limitation. Figure 11b shows that maximum power reached is obtained for cocurent flow for a little difference of 0.72 W, but maximum current intensity is given for values greater than 2.5A for crosscurrent flow.



**Figure 11.** Performance (a) and Power (b) curves for the PEMFC in operation a (♦) co-current flow, (■) contre current flow and 6 psi of cathode presion.

Figure 12a shows performance curves obtained with both flow types at 4 psi for cathodic pressure, so in this case the zone of activation loss is around 0.18A, so one can observe the difference in electrode activation related to their feeding flow. The zone of Ohmic loss is located at 0.18A and 0.21A, and the zone of diffusion loss seems to be similar in both feeding flow types. On the other hand the co-current (see figure 12b) continues to present a greater value than those presented by the crosscurrent flow, but this difference is as small as 0.033 W.



**Figure 12.** Performance (a) and Power (b) curves for the PEMFC in operation a (◆) co-current flow, (■) contre current flow and 4 psi of cathode presion.

In general a quasi-immediate activation process is observed for all cases where a crosscurrent was applied. This effect could be attributed to smaller concentration gradients of reagent gases over surfaces and between active faces for both electrodes (cell potential), so once the feeding zone for hydrogen is located, then the output oxygen zone is located, and that allows smaller potential gradients for both electrodes surface and for cell potential, that means between both electrodes. If we compare both flows, the feeding reagents zone has the same location, so a greater reagent concentration is expected around the mentioned zone along with a more intense potential, but on the output zone of residual gases the reagent concentration could be diminished due to the consumption of gases along the distribution channels that causes a slower activation due to the potential gradient between the feeding zone and the output zone. The same effect is observed for zone of diffusion loss, as shown in performance curves for the PEMFC for both flow types where a crosscurrent flow reaches greater current densities.

**Table 2.** Summary results for the experimental design in the PEMFC.

Flow	Pressure (psi)	Current (A)	Power (W)	Voltage (V)
Co-current	14	2.25	0.688	1
Counter current	14	2.63	0.682	0.825
Co-currente	10	2.57	0.759	0.99
Counter current	10	2.6	0.662	0.82
Co-currente	6	2.3	0.71	0.99
Counter current	6	2.56	0.618	0.81
Co-currente	4	2.11	0.63	0.99
Counter current	4	2.52	0.597	0.81

On the other hand, the electric power of the PEMFC demonstrates significant interaction due to the combined effect between cathodic pressure and the flow types in the reagent feed. The co-current flow applied in the feeding of reagent gases to the cell declares greater electric power levels for

cathodic pressures around 10psi, and we consider this effect could be attributed partially to an optimum pressure for the input of reagent gases and also for output products in the cathodic electrode. Also it is observed that a co-current flow can offer greater electrochemical activity at the feeding gases zone. Table 2 presents a summary related to variables studied in the experimental design applied to the designed PEMFC.

## 5. CONCLUSIONS

A PEMFC was designed and built in Faculty of Chemical engineering at BUAP and was characterized at the chemical department of CINVESTAV. Results obtained during its characterization allow us to conclude that input and output design for reagent gases by polar plates could provide a positive effect on PEMFC performance when ordering the flow profiles in feeding of reagent gases. With crosscurrent flow, greater densities of electrical current are observed, also almost an immediate activation on the PEMFC is presented at the mentioned conditions in the experiment; this effect can be attributed to a better distribution of reagent gases over the electrode surfaces, this has by itself an effect over the cell potential. On the other hand a co-current shows greater levels of electrical power generated by PEMFC at the operation conditions given in this work; this effect could be attributed to generation of more intense zones of activity (feeding zone of reagent gases) over the electrode surface as a function of the fluid type. And it is highly probable that as greater levels of cathodic pressure are applied, then a greater electric power would be generated in the PEMFC when it works in a counter current flow.

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