Preparation of porous gas diffusion electrodes with platinum catalysts for hydrogen/oxygen fuel cell

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abstract

A preparation method for porous gas diffusion electrodes with platinum nanoparticles supported on Vulcan XC-72 carbon is presented. A fabrication procedure to manufacture a membrane electrode assembly (MEA), including the gas diffusion layer and the active layer, to be used in hydrogen/oxygen proton exchange fuel cell are described. The design and construction of a single prototype of hydrogen/oxygen PEM fuel cell, which incorporates the assembly MEA developed in-house, are presented. The performance of this prototype is evaluated by measuring both polarization curves and power density. The experimental curves show the typical profiles of the fuel cell where different regions of energy losses, associated with limiting phenomena such as activation, ohmic, and concentration-controlled regions, are distinguished. The experimental power density curve presents a maximum power output of approximately 0.12 W cm-2 at a current of about 0.31 A cm-2. Preliminary results allow us to conclude that the preparation method for porous gas diffusion electrodes catalyzed with platinum nanoparticles as well as the development of MEA, are suitable to achieve an efficient performance of the prototype of hydrogen/oxygen PEM fuel cell.

**Keywords:** porous gas diffusion electrodes, platinum, fuel cell, energy.

1. INTRODUCTION

The most efficient way to use the chemical energy of hydrogen is its straightforward conversion to electricity in fuel cells through a highly efficient process [1, 2]. In other words, fuel cells directly convert the free energy of a chemical reaction into electrical energy [1, 3]. Even when considering the improvement introduced in different components of fuel cells [4-20], some advances on the development of catalytic materials are required in order to optimize the energy conversion processes.

The membrane electrode assembly (MEA) constitutes the heart of hydrogen/oxygen proton exchange membrane fuel cells (PEMFC) [4, 21]. It is composed by the electrolytic membrane and porous gas diffusion electrodes, which are attached to both sides of the membrane. Porous gas diffusion electrodes consist of three layers, that is, the carbon support layer, the hydrophobic gas diffusion layer, and the catalytic layer [21-23]. Due to the fact that porous gas diffusion electrodes are one of key components in fuel cells [6, 13, 21, 24], their composition and surface structure are fundamentally needed to obtain better results during fuel cell applications.

Structural characteristics of porous gas diffusion electrodes are crucial factors because of the limitations they impose over the whole performance of the fuel cell. Those electrodes are designed and developed for their usages as electrodes of hydrogen/oxygen fuel cells, since their complex structure makes them suitable enough in electrochemical reactions with reactant gases. One of the main features of such electrodes is to supply reactant gases with an easy access to active sites, providing high contact area between catalyst, molecules of reactant gases and electrolytic media. Thus, the typical structure and composition of porous gas diffusion electrodes make it possible to establish the three-phase boundary (catalyst/electrolyte/reactant gases) necessary for optimal operation of fuel cells [17, 25, 26]. In this regard, it has been noted that only catalyst particles that are in close contact with the electrolyte and the reactant gas are involved with electrodic reactions that occurs at the three-phase boundary [2, 17].

It is well known that platinum is the most effective catalyst for hydrogen/oxygen proton exchange membrane fuel cells (PEMFCs) [1, 2, 17]. To ensure maximum utilization, it is dispersed as nanoparticles on conductive carbon/teflon supports of high surface area, forming a catalytic layer or active layer of gas diffusion electrodes [1, 2].

In this work, a preparation method for porous gas diffusion electrodes with platinum nanoparticles supported on Vulcan XC-72 is presented. Then, a fabrication procedure to manufacture a membrane electrode assembly to be use in hydrogen/oxygen PEM fuel cells is described. After that, and based on porous gas diffusion electrodes developed in our laboratory, MEA is made. The design and construction of a single prototype of hydrogen/oxygen PEM fuel cell, with the incorporation of assembly developed in-house at laboratory scale, are presented. Finally, the results about the performance of the fuel cell prototype, measured by means of polarization curves and power density curves, are showed and evaluated.

2. MATERIALS AND METHODS

Porous gas diffusion electrodes developed in-house at laboratory scale consist of a gas diffusion layer which is highly porous and hydrophobicized with polytetrafluoroethylene (PTFE), and an active layer which contains the platinum catalyst supported on carbon. Generally, porous gas diffusion electrodes are prepared by using techniques that produce a highly porous structure over an electric conductive matrix. In other words, they are obtained by application of several components such as carbon, graphite, PTFE and catalytic metal particles [20, 25, 27]. Each of them belongs to a specific layer that constitutes the final structure of the porous gas diffusion electrode. A wider review of the different components and manufacturing methods of porous gas diffusion electrode can be found in the bibliography [10, 25-27].

In the present work, gas diffusion electrodes with three-layer structure (carbon support, gas diffusion layer and catalytic layer) were prepared by two steps. On the one hand, it was coating with a gas diffusion layer onto the carbon support, and on the other hand, it was coating with a catalytic layer onto the gas diffusion layer. A carbon cloth (CPW-003 Textron) was utilized as support and, over it, different inks were settled in order to give a final structure to the electrodes. The gas diffusion layer, deposited over the carbon cloth, was prepared by forming an ink that consists on a mixture of Shawinigan acetylene black, isopropyl alcohol, distilled water and PTFE suspension (TE-3893 DuPont). The purpose of adding PTFE at this step, is to provide not only a bonding between the carbon black but also to impart a hydrophobic nature to the gas diffusion layer. The active layer of the porous gas diffusion electrode, deposited over the gas diffusion layer, consists on a mixture of 20 weight percent (20 % wt) Pt nanoparticles (E-TEK, Inc.) supported on Vulcan XC-72 carbon and 5 weight percent (5 % wt) Nafion perfluorinated resin solution (Aldrich). The platinum loading of the porous gas diffusion electrode was 1 mg cm-2 on both the anode and cathode sides and the geometric area of the electrode was 4 cm2. The catalytic ink was uniformly deposited onto the surface of the gas diffusion layer previously formed. In all the cases, in order to apply the inks corresponding to the gas diffusion and the active layers, a brush painting technique developed in-house was utilized. This technique consists on successive applications of respective inks of each layer in a quantitative and manually way until reaching to the desired load onto each layer.

With the porous gas diffusion electrodes previously prepared, the assemblies MEA were developed. The proton conducting membrane Nafion 117 was chosen as the electrolyte membrane material. To make the membrane-electrode assembly MEA, the Nafion membrane was sandwiched by the same two porous gas diffusion electrodes under a 155 °C high temperature for 5 minutes and at 70 kg cm-2 pressure. The complete sequence of the fabrication procedure of porous gas diffusion electrodes and construction of MEA is shown in Figure 1.

Prior to assemble the electrodes to make the membrane-electrode assembly MEA, the Nafion 117 electrolyte membrane was pretreated by immersion in different aqueous media at 80 °C for 1 h. The pretreatment procedure includes the following immersion steps:

- distilled water to hydrate the membrane and to dissolve surface contaminants,

- 10 volume solution of hydrogen peroxide to remove organic impurities of the surface,

- triple distilled water to rinse previous solution,

- dilute sulfuric acid solution (1 molar) to remove metal impurities and to ensure that the membrane is protonated,

- distilled water to remove sulfuric acid traces and to hydrate the membrane.

Finally, the membrane was left into water before making the MEA.

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**Figure 1:** Fabrication sequence of porous gas diffusion electrodes and assembly MEA.

With the assembly MEA developed, a single prototype hydrogen/oxygen PEM fuel cell was built. In order to achieve optimal humidification of reactant gas inlet (particularly hydrogen gas), a gas bubbling system in hot water was designed. Thus, hydrogen gas inlet was saturated with water vapor by passing through a hot water system specifically developed for that purpose (Figure 2). Hydrogen gas was humidified by bubbling through a water reservoir held at 90 °C and oxygen gas was supplied to the cathode at ambient temperature. A slight excess of reactant gases hydrogen and oxygen, with respect to the calculated by Faraday’s Law, was used [26].

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**Figure 2:** Schematic illustration of the gas humidification by a gas bubbling system in hot water.

The fuel cell tests at 60 °C and 1 atm gas inlet pressure were performed. The performance of the fuel cell prototype was evaluated by measuring the polarization curves (E-i) and the power density curves (P-i), using an especially equipment developed in-house. The polarization curve shows the working cell potential of the fuel cell (E) as a function of the current density (i). It was obtained by changing the cell potential and measuring the stationary response with the current density, for a particular set of conditions under which the cell is operated. The power (P) delivered by the fuel cell is given by the product of the current (I) and cell potential (E). The fuel cell power density curve (P-i), which gives the power density delivered by the fuel cell as function of the current density, was constructed from the information of the polarization curve of the fuel cell. The power density curve is produced by multiplying the cell potential at each point on the E-i curve by the corresponding current density [1]. The full procedure for the development of the porous gas diffusion electrodes, assembly MEA, fuel cell prototype, and also their evaluation, were described as part of the results obtained.

3. RESULTS AND discusSiOn

In this section, the obtained results from each part of porous gas diffusion electrodes developed in-house at laboratory scale are described and discussed: the gas diffusion layer, the active layer, and the development of the assembly MEA. Finally, the construction and the performance of a single prototype of hydrogen/oxygen PEM fuel cell, which utilizes the developed assembly MEA, are described.

The structure of gas diffusion electrodes developed in-house is formed by three layers:

- First layer (carbon cloth layer): which is in contact with the gas phase. The carbon cloth serves as a structural support for others layers as well as current collector.

- Second layer (gas diffusion layer): makes a contribution for the gases to go to the following active site of the next layer.

- Third layer (active or catalytic layer): which contains platinum catalyst and where the electrochemical reactions take place.

Figure 3 shows the schematic structure of the porous gas diffusion electrode with carbon matrix developed in-house, where the typical three-layer structure mentioned above is distinguished.

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**Figure 3:** Schematic illustration of porous gas diffusion electrode structure.

Porous gas diffusion electrodes developed in-house at laboratory scale have a complex structure that simultaneously satisfies several requirements for the optimal performance of the fuel cell prototype [1, 2]. It is necessary to highlight that, as the electrodes are systems with a very complex microscopic structure, the operational features (referred to the optimal operating conditions such as temperature, gas pressure, etc.), which highly depend on the components used for the electrode fabrication and on the characteristics of the fabrication process, will be studied here.

The durability and performance of porous gas diffusion electrodes used in fuel cells depend on the fabrication procedure and final structure obtained by the different layers that conform these electrodes, and they are prepared according to a mixture of carbon, polytetrafluoroethylene (PTFE), and catalyst [25-27], as well as mechanical and chemical degradation effects [10, 28]. Hence, the importance of this work, is the fabrication procedure of porous gas diffusion electrodes for their uses in hydrogen/oxygen PEM fuel cells, capable of keeping the compromise between necessary properties for the optimal operation of these electrochemical devices, manufacture costs and long-time operation.

**3.1 Gas diffusion layer**

The gas diffusion layer is obtained by depositing a specially prepared ink over carbon cloth CPW-003 from Textron. That ink is elaborated from Shawinigan acetylene black dispersed in isopropyl alcohol by a soft stirring, wetted with distilled water and by adding PTFE suspension (TE-3893 DuPont). PTFE behaved as a hydrophobic agent by providing channels for the water transport and, at the same time, by serving as an agglomeration agent giving structural support to the electrode. PTFE content in the gas diffusion layer was 34 weight percent (34 % wt), expressed in terms of the total mixture weight. The carbon/PTFE ratio has great incidence during the gas diffusion layer-development since a low amount of PTFE do not give enough structural strength to the electrode. On the other hand, high amounts of PTFE can block the pores by preventing the gas for being transported through the electrode structural matrix and negatively impacting on the fuel cells performance [26, 29]. The amount of PTFE used at this stage, was according to the results indicated by some authors [22, 30], who reported optimum values about 30-35 %. By stirring the prepared ink at ultrasonic bath, its homogenization was reached. For the formation of the gas diffusion layer, the ink above described is brushed on both side of carbon cloth onto heated plate at 100 °C, left to dry for 2 minutes and rolled one time, in order to ensure the electrode uniformity. After the rolling process, the ink was brushed again. As a result of the successive brushing, a 4 mg cm-2 ink content in the gas diffusion layer was obtained. The final structure is heated at 300 °C by thermal treatment in an oven for 15 minutes and rolled one time. Then, thickness of the gas diffusion layer at 20 fixed positions was measured and averaged with a high precision micrometer. A 100 μm value was obtained, consistent with the values reported in the bibliography [1, 24, 25]. A thin gas diffusion layer, with less resistance to electricity, was developed to allow an easy flow of hydrogen and oxygen reactant gases through the structure of the electrode. Gas diffusion layer characteristics, achieved by the brushing procedure of successive layers until the desired amount was reached, allowed to obtain an adequate structure of the electrodes that favored the distribution and scope of the reactant gases to the reaction side. The developed gas diffusion layer was used as the base substrate for the deposition of platinum catalysts.

3.2 Active layer

The active layer is obtained by application of a prepared ink based on a mixture of 20 weight percent (20 % wt) commercial Pt nanoparticles (E-TEK, Inc.) supported on Vulcan XC-72 carbon and 5 weight percent (5 % wt) Nafion perfluorinated resin solution (Aldrich). Nafion content in the active layer is 2.8 mg cm-2, representing a 35 weigh percent (35 % wt) expressed in terms of the total weight of the mixture. The solid content of the ink is defined as the percentage of the mass of solid in the ink, divided by the total mass of the ink. This gives an indication about how thick the ink is. For the electrode developed in-house at laboratory scale, it was found that the Nafion content used in their fabrication procedure was optimal because we achieved minimize typical mass transport and ohmic losses overpotentials of electrodes, as the bibliography suggests [25, 26]. It is well known that an appropriate Nafion content in the catalytic layer is necessary for a satisfactory performance of fuel cells [1]. Nafion ionomer content in the catalytic layer of our electrodes helps to retain moisture and to prevent membrane dehydration, especially at high current densities. It contributed to reach a good permeability of gases and to reduce the ionic resistance because pores were filled with Nafion, which is a polymer with ionic conductivity properties. Besides, an increment of the electrochemical active area in electrodes was accomplished with Nafion in the active layer improving the global performance of electrodes and; consequently, that of the fuel cells.

In this work, the platinum loading in the active layer was 1 mg cm-2. The obtained ink was agitated at ultrasonic bath for 2 hours and then it was quantitatively applied by brushing onto one side of the gas diffusion layer previously developed, forming the active layer. Finally, the layer was impregnated with Nafion solution in order to promote the three-phase boundary, which was required for the electrochemical reaction to take place. Immediately after the impregnation process, the final structure was heated at 100 °C in a thermal treatment plate for 5 minutes. The definite thickness of active layer, determined by a high precision micrometer at 20 different fixed positions, was 43 μm on average. As a result, the difference between the total thickness of the electrode and that one of the gas diffusion layer was obtained by difference.

According to successive experimental tests for fabrication procedure of porous gas diffusion electrodes, optimum rheological characteristics and proper consistency of different inks of gas diffusion and active layers, were achieved.

3.3 Membrane Electrode Assemblies (MEA)

Assemblies MEA were fabricated from porous gas diffusion electrodes previously prepared. A schema of the assembly MEA is depicted on Figure 4.

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**Figure 4:** Detailed schema of each one of the parts that constitute the assembly MEA.

The electrodes, anode and cathode, were symmetrically placed on both sides of the Nafion proton conducting membrane. Thus, the Nafion 117 membrane was disposed between the electrodes and active layer in intimate contact with the membrane forming a "sandwich" like structure (anode-Nafion membrane-cathode). In order to form MEA, the assembly electrode-membrane-electrode was put between two metal sheets and then they were hydraulic pressed with heated plates under 70 kg cm-2 of pressure at 155 °C, for 5 minutes. The whole MEA was sealed by two layers of a gasket material (top gasket and bottom gasket). Figure 5 shows the assembly obtained with their dimensions and gasket material, which provide a seal around the MEA to prevent leakage and mixing of reactant gases.

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**Figure 5:** Assembly MEA developed at laboratory scale.

Thickness difference between porous gas diffusion electrodes (anode + cathode) and Nafion membrane is compensated with the gaskets. At the same time, it acts as spacers avoiding an inappropriate compression of the assembly electrode-membrane when they are placed between the conductor graphite plates build the fuel cell prototype.

In general, because the bond between electrode-membrane is generated by a hot-pressing technique, one of the most usual problems is the relative low contact area between the membrane and the catalyst layer. In experimental tests for the assembly MEA to made, by visual and manual inspections, an optimal union between porous gas diffusion electrodes and Nafion 117 membrane was verified. The pressure and temperature of the hot-pressing technique, selected to the assembly MEA preparation, were adequate because they did not affect the bonding of the electrodes with the membrane during MEA preparation. Heat and pressure were properly applied because there were not curvatures introduced into the electrodes that could have affected the performance of the fuel cell. The efficient contact between electrode-membrane, as well as the structure and final composition of porous gas diffusion electrode, avoided mass transport issues in interfaces of different components [25, 26], which usually lead to produce efficiency loss of fuel cells.

Through brushing and hot-pressing techniques, used on the development of the different layers of porous gas diffusion electrodes and MEA, a good contact between the active layer and membrane can be obtained, resulting in both a lower ionic resistance and worth cell performance. This can be evidenced by experimental results that are shown in curves presented in the next section, when the fabricated electrodes are used to study the performance of the developed fuel cell prototype, showing the typical behavior of the hydrogen/oxygen PEM fuel cell, according to the data reported in the bibliography [1, 2, 24].

3.4 Prototype of fuel cell

A single prototype of hydrogen/oxygen PEM fuel cell was built from the assembly MEA previously developed, as it is shown in Figure 6.

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**Figure 6:** Schematic depicting of fuel cell prototype designed in-house at laboratory scale.

In this schematic depicting, each one of the parts that constitute the prototype of the fuel cell developed in-house at laboratory scale is indicated. The fuel cell prototype is integrated by two conductor graphite plates, where inlet and outlet reactant gases holes are turned, as well as those for the thermocouples. Graphite plates are machined with serpentine flow channels. The assembly MEA is placed between the conductor graphite plates together with the gasket. Immediately after, and on both sides of the conductor graphite plates, copper current collector plates are located. Separated by insulating material, aluminum plates are placed, which allow the complete closure of the prototype to be adjusted by screws. The fuel cell prototype is warmed up by heating resistances, which are in intimate contact with aluminum plates and inserted into it. Heating resistances are controlled by specific test equipment software that allows to select the operation temperature of the fuel cell by means of a computational command and to keep it constant with an error minor to ± 0.1 °C. The temperature sensor is located in a strategic place of the fuel cell so the software identifies temperature variations of the fuel cell quickly and responds immediately to these changes. Thus, by switching resistances on and off, the temperature is maintained at a desired set value (60 °C).

F:\SILVINA R IMAM\REVISTAS\Revista Materia 2021\Figuras definitivas\FIG. 5 - copia.tifExperimental data of the polarization curve (E-i) and power density curve (P-i) showing the performance of the fuel cell, are presented in Figure 7. In this figure, current densities are referred to the 4 cm2 geometric electrode area. The fuel cell prototype exhibits an open circuit potential of 0.96 V, which is less to the one found in the bibliography for a typical hydrogen/oxygen PEM fuel cell, that is to say 1.23 V [1] (which is the open circuit potential value with no energy losses). The different values are related to the energy losses of the irreversible reactions [1, 29]. This suggests a slight decrease in the reversibility of the oxygen electroreduction when the platinum catalyst is used in the fuel cell assemblies.

**Figure 7:** Polarization curve (●) and power density curve (◊) of the fuel cell prototype. Active anode area=4 cm2 with 1 mgPt cm-2, Tcell=60 °C, pressure=1 atm.

The experimental polarization curve shows the typical profiles of the hydrogen/oxygen PEM fuel cell, where different regions of energy losses, associated with the limiting phenomena, are distinguished. In other words: (a) activation, (b) ohmic, and (c) concentration-controlled region (Figure 7 (●)). In the polarization curve, at low current densities, the activation-controlled region can be distinguished. This region corresponds to the energy losses related to the charge resistance transference and associated chemical reactions (kinetic losses) that are part of both the natural function and surface structure of the catalyst. In the activation-controlled region, a typical precipitous drop of the cell potential was observed, due to the sluggish kinetics of the electrodic reactions on the surface of the electrodes [29]. This behavior is particularly associated with the oxygen electroreduction reaction [29]. In the polarization curve, at medium current densities, the ohmic-controlled region was observed. It represents the energy losses related to the ion flow resistance in the electrolyte, to the electrons through the electrode, and to the contact resistance [31-33]. In this region, the fulfillment of Ohm’s law is verified showing a potential drop that is proportional to the current density. In the polarization curve, at high current densities and within the concentration-controlled region, effects of mass transport due to limitations of gas reactive transport to pores, of gas diffusion and active layers takes precedence, producing an inevitable drop of the fuel cell performance [29, 31, 33]. In this region, a drop of cell potential was observed, related to deficient supplies of reagents to active catalytic sites.

The experimental power density curve, obtained by the fuel cell prototype developed in-house at laboratory scale and also shown on Figure 7 (◊), presents a maximum power output of approximately 0.12 W cm-2 at a current of about 0.31 A cm-2. The power density curve showed an increase of the power (P) with the increment of the current density (i), until reaching a maximum power output (Pmax) that determines the maximum power for unitary area of the fuel cell (W cm-2) for the operating conditions of the prototype. This maximum power output value is due to the commitment between the power increase (P) with the increment of the current density (i) and the provision of the reactive gas towards the reaction sites until reaching the maximum power. After that, the Pmax drop derives from the depletion of the reactant gases when the current increases [29-33]. In experimental tests realized on the fuel cell prototype, a good cell performance was observed, without any drastic decrease of power for the operative conditions under study.

When the test periods on the fuel cell finished, the assemblies MEA were found intact. After disassembling the fuel cell prototype, the electrodes had a crack-free surface, without evidence of ruptures, perforations or non-uniformity surface. So, it can be affirmed that the technique used for the design and fabrication procedure of the porous gas diffusion electrodes has been adequate to obtain good results in the operation of the fuel cell prototype.

The PTFE content used in the fabrication procedure of porous gas diffusion electrodes was appropriate because the electrodes stayed intact even after the MEA press heating. It usually occurs by the dilatation and accumulation of tensions that are then released by destroying the assembly with mechanical degradation effects [28]. On the other hand, the PTFE loading used in the general development of electrodes also helped to maintain the water balance in the membrane, allowing to keep the appropriate water content and drain the excess for a good performance of the fuel cell [34].

In order to achieve a high performance of the fuel cell prototype, an appropriate water management is critical [1, 34]. In fuel cells tests, water was introduced by external humidification of the hydrogen gas and also as a product of the oxygen reduction reaction at the cathode side. Through this procedure, an optimal humidification of gas inlet for suitable operation of the fuel cell was reached, allowing a good performance of the fuel cell prototype. The final structure of gas diffusion electrodes developed in our laboratory, also helped with the proper water management in the membrane and catalytic layer by rejecting the excess of water formed at the cathode or retained water for proper membrane hydration, directly affecting the performance of the fuel cell. The pressure of inlet reactant gases was enough to maintain the intensive work of the fuel cell prototype. Flooding of electrodes, that would lead a drop in the performances of the fuel cell, was not observed.

Experimental tests carried out on the fuel cell prototype development within in-house at laboratory scale allowed to identify the process for porous gas diffusion electrode fabrication as optimal, around which the construction of the overall assembly MEA and fuel cell prototype can be continually designed and developed. From all the mentioned above, it was possible to verify that the design and fabrications of porous gas diffusion electrodes were suitable to provide a high contact area between the active sites of catalysts, the molecules of reactant gases, and electrolytic membrane, forming the necessary three-phase boundary for a good performance of the electrodes and fuel cell prototype.

4. CONCLUSIONS

A fabrication process to manufacture a porous gas diffusion electrodes catalyzed with platinum nanoparticles supported on carbon Vulcan XC-72 was presented. With these electrodes, membrane electrode assemblies (MEA) to be used in a single prototype of hydrogen/oxygen PEM fuel cell, were fabricated. The structure and composition of the electrodes were optimized by using information from polarization curves, power density curves, and fuel cell test measurements. The final structure of porous gas diffusion electrodes developed in our laboratory, basically the micro porosity and hydrophobic nature, allowed the diffusion of reactant gases to be uniformly led towards the surface of the platinum catalyst. The fuel cell prototype was designed and developed in-house at laboratory scale. The performance of the fuel cell prototype was evaluated by measuring the cell potential and power density curves as a function for the current densities. Preliminary tests performed at 60 °C showed a good cell performance of the prototype and good stability during the operation time, without any evidence of sintering nanoparticles but always preserving the integrity of all the electrodes components. It was concluded that the fabrication procedure of porous gas diffusion electrodes by brushing, high temperature sintering, and hot-pressing techniques for assemblies MEA preparation are suitable for an efficient performance in a single prototype of hydrogen/oxygen PEM fuel cell developed in-house at laboratory scale. Porous gas diffusion electrodes developed by this technique performed well. Nonetheless, more in-depth research is needed to further increase the performance of the fuel cell prototype.

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