

# THE POLYMER ELECTROLYTE MEMBRANE FUEL CELL AS ELECTRIC ENERGY SOURCE, STEADY STATE AND DYNAMIC BEHAVIOR

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**Abstract** - The main objective of this work is to give information on the behavior of three small PEMFC (*Polymer Electrolyte Membrane Fuel Cell/Proton Exchange Membrane Fuel Cell*) prototypes under static and dynamic load conditions. This is a fuel cell that holds promise in the use for energy in automotive and household applications. A computational model was developed to simulate the static and dynamic performance of this particular type of fuel cell. This model is based on electrochemical equations and takes into consideration the advantages and disadvantages of the device in order to generate power. The model takes into consideration the operating and design parameters of the materials, with the results being compared with practical experiments.

This research gives the possibility to infer, from steady state and dynamic studies, on the design of PEMFC's of different sizes and also to develop a further research on the need for control such as of hydrogen and oxygen pressure and flow. The study of sizing of the fuel cell is also an invaluable asset due to the low cost of the simulation.

**Keywords** – alternative energy, distributed generation, dynamic studies, proton exchange, polymer electrolyte, steady state.

## 1. Introduction

Fuel cells are similar to batteries; the difference is that they work continuously producing the current through an electrochemical natural reaction taking hydrogen based fuel in the anode, oxygen in the cathode and producing electricity, heat and vaporized water. Its electrochemical operating principle is the opposite of the electrolysis.

The basic physical structure of a fuel cell consists of an electrolyte and polymeric membrane (with typical thickness between 12 and 210  $\mu\text{m}$ ) that separates the porous anode and cathode from each other; they have thickness between 5 and 15  $\mu\text{m}$ . The porous and thin electrodes, make it possible to assemble it together with the polymeric membrane, making an integrate set called MEA - Membrane Electrode Assembly. In a typical fuel cell, a flux of fuel rich in hydrogen (liquid or gaseous) is fed continuously through channels that keep it in contact

with the anode and, simultaneously, a flux of an oxidant (in general the oxygen in the air) also fed through channels, make the contact with the cathode. [1] The baking layers are responsible for the gas diffusion process in the electrodes, with a thickness between 300 to 400  $\mu\text{m}$ , they are made of an electrical conductor material, like porous carbon paper, a carbon based fabric with a Teflon<sup>®</sup> layer that prevents water adherence and make possible the fast diffusion of gases. [2]

The process that takes place is a natural reaction, however due to its low speed it is necessary the use of a catalyst around the electrodes for the reaction to be efficient, the element used as catalyst at the present is the platinum. Other two important elements in the fuel cell are, firstly the separating plates, to give mechanical rigidity and to direct the flow of gas through the cell, secondly the refrigeration cells that have the function to extract the heat of the exothermal reaction, the ratio used for interspersing the refrigeration cells among fuel cells are used in a proportion that varies from 1:1 to 1:5.

### A.. PEM fuel cells

The PEMFC (*Polymer Electrolyte Membrane Fuel Cell / Proton Exchange Membrane Fuel Cell*) are fuel cells where the electrolyte is made of an organic polymer that has the characteristic of a good proton carrier when in presence of a water solution.

The only liquid existent in this kind of cell is water and, therefore, the corrosion problem is minimum. The water management in PEMFC cells is extremely important. The fact that the membrane needs to be always in water solution, will limit the temperature of the cell operation to the water vaporization temperature, avoiding membrane dryness. Not allowing energy co-generation from the thermal energy dissipated. The efficiency of the whole process is around 50% to 60%.

The main initial difficulty to the use of PEMFC cells was the high cost of the platinum necessary as a catalyst in

the electrodes. Initially the PEMFC cells used 4 mg of platinum per cm<sup>2</sup> of membrane area that made expensive the use of this kind of cell. Nowadays, with the technological development in the materials for the electrodes it is possible the use of 0.15 mg/cm<sup>2</sup> of platinum, with the same electrical efficiency, making the fuel cell less expensive and closer to the economical viability.[8]

The PEMFC's have a robust design and are relatively simple to build. The main characteristics are the low operating temperature (≈80°C) that allows a fast response when being turned on and off. To these properties can be added the advantages of the direct utilization of air in the cathode and zero emission of CO<sub>x</sub> and NO<sub>x</sub>, making this type of cell the most promising alternative for the substitution of the combustion engines used in transportation vehicles, and for the electrical energy production in small and medium size stationary units below 250kW.

The number of fuel cells in the array determines the value of the operation voltage in a fuel cell stack. The voltage is also defined by the internal losses, materials, assembling methods, the current intensity imposed by the load and the whole operational process. Therefore, the electric power generated by the stack is defined by a series of assembling and operational parameters.

## 2. Mathematical Modeling of the PEM Fuel Cell

A mathematical model that presents correct answers for the fuel cell is of paramount importance, since it allows the development of electronic systems for feeding and to control for fuel cells without the need of a great number of experimental prototypes. A fuel cell works basically as a current source. The voltage response for the cell will be studied from the current variation required by the load. The main operational parameters are: *the operational electrical current (I<sub>op</sub>)*, *temperature (T<sub>op</sub>)*, and *the transportation of gases*. With the main parameters involved in the gas feeding system being:

$P_{H_2}$  and  $P_{O_2}$  – Partial pressure feeding for Hydrogen and Oxygen (in atm);

$\phi_{H_2}$  and  $\phi_{O_2}$  – Relative humidity of Hydrogen and Oxygen (in percent);

$m_{H_2}$ ,  $m_{O_2}$  and  $m_{Air}$  – mass flow of Hydrogen, Oxygen and Air (dimensionless);

$\lambda_{H_2}$ ,  $\lambda_{O_2}$  and  $\lambda_{Air}$  – Stoichiometries of Hydrogen, Oxygen and Air (dimensionless).

### A. PEM fuel cell with static load

The electrical behavior of a PEM fuel cell is obtained from the maximum voltage that can be produced by one cell ( $E^0$ ) and by the existing energy losses during normal operation.

Among the main losses to be considered are: the activation ( $V_{atv}$ ) and concentration ( $V_{con}$ ) effects in the anode and in the cathode, and the voltage drop due to the resistance of the cell ( $V_{ohm}$ ), each of them predominantly occurs during an operational load (value of electrical current) of the cell, producing a typical behavior.

The cell operational voltage ( $V_{op}$ ) can be computed through the open circuit voltage ( $E^0$ ), and internal voltage drops. Given by:

$$V_{op} = E^0 - (V_{atv} + V_{ohm} + V_{con}) \quad [V] \quad (1)$$

where  $V_{atv}$  are the activation losses,  $V_{ohm}$  are the resistive losses and  $V_{con}$  are the concentration losses.

### 1) Open circuit voltage or ideal voltage

The maximum value of produced voltage (open circuit voltage, reversible voltage or ideal voltage) in a fuel cell is an specific amount from the global reaction that occurs in the cell. In the case of a PEMFC cell, this can be calculated by the energy difference between the initial states of reagents ( $H_2 + \frac{1}{2} O_2$ ) and the final result ( $H_2O$ ). The maximum voltage produced by the cell for the reaction occurred ( $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ ) will be calculated through the Nernst expression:

$$E^{Nernst} = \frac{1}{2F} \{ \Delta G + \Delta S \cdot (T_0 + T_{ref}) + R \cdot T_{op} \cdot [ \ln(P_{H_2}) + 1/2 \cdot \ln(P_{O_2}) ] \} \quad [V] \quad (2)$$

Where  $F$  is the so-called Faraday constant (96.487 C),  $\Delta G$  is the variation of Gibbs free energy (-237.165 J),  $\Delta H$  and  $\Delta S$  are respectively the variation of enthalpy (-285.823 J) and entropy (-163.2 J/K) in the reaction,  $R$  is the gases universal constant (8,314 J/°K.mol), and  $T_{ref}$  (298.15 °K) and  $T_{op}$  are respectively the reference and operational temperatures in °K.

By the application of constants to the Nernst maximum voltage equation can be simplified to:

$$E^0 = 1.229 - 0.85 \cdot 10^{-3} \cdot (T_{op} - 298.15) - 4.31 \cdot 10^{-3} \cdot T_{op} \cdot [ \ln(P_{H_2}) + 1/2 \cdot \ln(P_{O_2}) ] \quad [V] \quad (3)$$

with this equation, it is made the relationship of the ideal voltage with the main operational variables (operating temperature and the feeding pressures of hydrogen and oxygen), the remaining variables are not significant to the maximum operating voltage.

### 2) Activation effects

The activation voltage drop ( $V_{atv}$ ) is dominant in the initial stage of chemical reaction, that is, when the current density in the cell is low. Those are effects that change with the increase in current density. The activation voltage drop can be defined by the Tafel equation:

$$V_{atv} = \frac{R T_{op}}{\alpha n F} \ln \left( \frac{j_{op}}{j_0} \right) \quad [V]. \quad (4)$$

Where  $R$  is the gases universal constant (8,314 J/K.mol),  $n$  is the ratio between the number of moles involved in

this reaction for each mol of H<sub>2</sub> (a typical value is 2),  $j_{op}$  is the cell operation current density,  $j_0$  is the exchange current density in the electrode (typical values are around 0.5 A/cm<sup>2</sup>), and  $\alpha$  is the electronic transference current (around 0.4 for the cathode and 1.0 for the anode) that represents the proportion of energy available at the electrode that is used in the electrochemical reaction.[13]

### 3) Ohmic effects

The cell ohmic resistance occurs due to two distinct factors: the resistance that the electrolyte (polymeric membrane) offers to the ionic flux and the resistance offered by the electrodes ( $R_m$ ), and the resistance of gas spreaders and separating plates to the flux of electrons ( $R_{cj}$ ). We can consider that the ohmic losses ( $V_{ohm}$ ) in the cell as:

$$V_{ohm} = (R_m + R_{cj}) \cdot i_{op} \quad [V] \quad (5)$$

### 4) Concentration effects

On the other hand, every time that one of the reagents is consumed by the electrochemical reaction in the cell electrodes, the cell doesn't have the capacity to keep the initial concentration in the neighborhood of the electrode. This reagent concentration effect gradient, close to the electrode produces a decrease in the cell electrical voltage named concentration effect. The concentration voltage drop ( $V_{con}$ ) can be calculated by the equation:

$$V_{con} = \frac{RT_{op}}{nF} \ln \left( 1 - \frac{i_{op}}{i_L} \right) \quad [V] \quad (6)$$

Where  $i_{op}$  is the operational cell current and  $i_L$  is the electrode current limit. They both have different values to the cathode ( $i_{L,c}$ ) and anode ( $i_{L,a}$ ). The  $i_L$  values will depend on the assembling conditions, as the cell area, shape of channels that drive the gas internally in the cell, gas spreader characteristics, type of membrane, and etc.[4][6]

## B. Activation losses

### 1) Cathode activation losses

Observing equation (4) in detail, the consideration on the effect of operating variables in the value of  $i_0$  in the cathode can be taken as[5]:

$$i_{0c} = n_c \cdot F \cdot A \cdot k^0 \cdot (C_{proton}^*)^{1-\alpha_c} \cdot (C_{H_2O}^*)^{\alpha_c} \cdot (C_{O_2}^*)^{1-\alpha_c} \cdot e^{\left(\frac{-\Delta FE_c}{R \cdot T_{op}}\right)} \quad (7)$$

for the cathode,  $n_c$  is the reagent number of moles,  $\Delta FE_c$  is the reaction activation energy (J/mol),  $A$  is the net area / useful area of the cell (cm<sup>2</sup>),  $\alpha_c$  is the load transference coefficient (not dimensional),  $k^0$  is the intrinsic constant reaction degree (cm/s),  $C_{proton}^*$  is the total concentration of protons in the membrane (mol/cm<sup>3</sup>),  $C_{H_2O}^*$  is the water concentration in the membrane (mol/cm<sup>3</sup>) and  $C_{O_2}^*$  is the Oxygen concentration in the interface

electrode/membrane (mol/cm<sup>3</sup>).

Working mathematically in equations (3) and (7) together, we can have for the cathode the following value for the activation voltage[3]:

$$V_{avc} = \xi_1 + \xi_2 \cdot T_{op} + \xi_3 \cdot T_{op} \cdot \ln(C_{O_2}^*) + \xi_4 \cdot T_{op} \cdot \ln(i) \quad (8)$$

where:

$$\xi_1 = \frac{\Delta FE_c}{n_c \cdot \alpha_c} \quad (9)$$

$$\xi_2 = \frac{R}{n_c \cdot F \cdot \alpha_c} \ln(4Fk^0) + \frac{R}{n_c \cdot F \cdot \alpha_c} \ln(A) + \frac{R}{n_c \cdot F} \ln(C_{H_2}^*) \quad (10)$$

$C_{H_2}^*$  - hydrogen concentration in the interface electrode/membrane (mol/cm<sup>3</sup>),

$$\xi_3 = \frac{R(1-\alpha_c)}{n_c \cdot F \cdot \alpha_c} \quad (11)$$

and

$$\xi_4 = \frac{R}{n_c \cdot F \cdot \alpha_c} \quad (12)$$

### 2) Anode activation losses

With a more detailed equation (7), taking in consideration the effect of operational variables in the value of  $i_0$  at the anode as[5]:

$$i_{0,a} = n_a \cdot F \cdot A \cdot k^0 \cdot C_{H_2}^* \cdot e^{\left(\frac{-\Delta FE_a}{R \cdot T_{op}}\right)} \quad [A] \quad (13)$$

where:  $n_a$  - number of moles of reagent at the anode;  $\Delta FE_a$  - reaction activation energy at the anode (J/mol);  $A$  - anode area / cell useful area (cm<sup>2</sup>);  $\alpha_a$  - load transference coefficient at the anode (not dimensional);  $k^0$  - reaction degree intrinsic constant (cm/s);  $C_{H_2}^*$  - hydrogen concentration in the interface electrode membrane (mol/cm<sup>3</sup>);

Working mathematically in equations (4) and (6) together, we can have for the cathode the following value for the activation voltage[4]:

$$V_{av,c} = \xi_5 + \xi_6 \cdot T_{op} \cdot \ln(C_{H_2}^*) + \xi_7 \cdot T_{op} \cdot \ln(i) \quad [V] \quad (14)$$

where:

$$\xi_5 = \frac{\Delta FE_a}{n_a \cdot F \cdot \alpha_a} \quad (15)$$

$$\xi_6 = \frac{-R \cdot \ln(n_a \cdot F \cdot A \cdot k^0)}{n_a \cdot F \cdot \alpha_a} \quad (16)$$

$$\xi_7 = \frac{R}{n_a \cdot F \cdot \alpha_a} \quad (17)$$

As previously stated, the activation voltage at the anode will have lower values compared with the activation voltage at the cathode, and can be neglected in the operating behavior of the PEM Fuel Cell fed with pure hydrogen.

### C. Resistive losses

To illustrate the empirics to obtain fuel cell operating parameters, the first part of the resistive losses ( $R_{ohm}$ ) is given by the polymeric membrane and the second part by the electrodes, spreaders and other series components.

#### 1) Polymeric Membrane Resistive Losses

The resistance in Ohm for this membrane ( $R_m$ ) which represents the resistance for transference of protons through the solid membrane, and can be computed by the two following equations:

$$R_m = \frac{\rho_m \cdot \ell}{A} \quad [\Omega] \quad (18)$$

Where  $\rho_m$  is the resistivity of the membrane ( $\Omega \cdot \text{cm}$ ),  $\ell$  is the membrane thickness (cm) and  $A$  is the membrane area, the electrode area. The resistivity values for the Nafion<sup>®</sup>[7] membranes (produced by DuPont) can be computed through the following equation:

$$\rho_m = \frac{181.6 \left[ 1 + 0.03 \left( \frac{i_{op}}{A} \right) + 0.0062 \left( \frac{T_{op}}{303} \right)^2 \left( \frac{i_{op}}{A} \right)^{2.5} \right]}{\left[ \lambda - 0.634 - 3 \left( \frac{i_{op}}{A} \right) e^{4.18 \left( \frac{T_{op} - 303}{T_{op}} \right)} \right]} \quad [\Omega \text{cm}] \quad [19]$$

For the Nafion<sup>®</sup> membrane, the typical thickness in each case is indicated in Table I.[8]

Table I – Typical thickness of Nafion membranes

Membrane	Nominal thickness (mm)	Thickness when dry (mm)	Thickness when wet (mm)	Thickness when MEA (mm)
Nafion 117	0,178	0,183 ± 0,003	0,208 ± 0,005	0,148 ± 0,002
Nafion 115	0,127	0,141 ± 0,003	0,161 ± 0,003	0,100 ± 0,002
Nafion 113	0,089	0,091 ± 0,002	0,111 ± 0,002	0,075 ± 0,003
Nafion 112	0,051	0,050 ± 0,002	0,058 ± 0,003	0,040 ± 0,002

Therefore,  $\lambda$  is the ratio of the number of water moles for each sulphonic group in the membrane. The value of  $\lambda$  indicates the membrane relative humidity, being regulated by the feeding gases relative humidity, their stoichiometries and assembling characteristics involved in the efficiency of the gas transport and membrane humidity maintenance. The literature indicates a value of approximately 14 for  $\lambda$  corresponding to a membrane in humidified air at 100%, and approximately to 22 the value corresponding to a water immersed membrane[3].

For the simulation, the value for  $\lambda$  will be calculated through an empirical equation with assembling parameters being influenced by operating variables, being the most important the values of feeding gases relative humidity and their stoichiometries.

### D. Concentration losses

#### 1) Concentration losses at the cathode

The value for the current limit at the cathode ( $I_{L,c}$ ) will be adopted[13] through the following equation:

$$i_{L,c} = \frac{R \cdot T_{op} \cdot A \cdot \gamma \cdot C_{ion,m}}{n_c \cdot F \cdot \delta_c} \quad [\text{A}] \quad (20)$$

where:  $n_c$  - number of moles of the reagent in the cathode;  $\gamma$  - membrane ionic conductance (Siemens.cm<sup>2</sup>/mol);  $A$  - cathode area / cell useful area (cm<sup>2</sup>);  $\delta_c$  - Nernst diffusion layer thickness at the cathode (cm);  $F$  - Faraday constant (96487 C/mol);  $R$  - gases universal constant (8,314 J/K.mol);  $T_{op}$  - cell operation temperature (°K);  $C_{ion,m}$  - membrane ionic concentration (mol/cm<sup>3</sup>).

#### 2) Concentration losses at the anode

They will be simulated as in equation (20), and the value for the current limit at the anode ( $I_{L,a}$ ) will be adopted through the following equation:

$$i_{L,a} = \frac{R \cdot T_{op} \cdot A \cdot \gamma \cdot C_{ion,m}}{n_a \cdot F \cdot \delta_a} \quad [\text{A}] \quad (21)$$

where:  $n_a$  - number of moles of the reagent in the anode;  $\delta_a$  - Nernst diffusion layer thickness at the anode(cm).

### E. PEMFC cell in a dynamic load regimen

When a variation occurs in the load fed by a fuel cell, this is the cause for a variation in the cell operating voltage. However, a transient regimen exists due to the capacitance generated in the polymeric membrane due to an internal physical process called “double layer effect”. Taking into consideration the influence of this capacitance, the equivalent circuit for the PEMFC fuel cell can be depicted in a simplified form, for constant pressure, as can be seen in Figure 1.

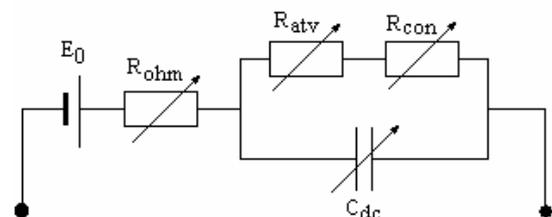


Fig. 1. Simplified electrical circuit for the PEM fuel cell.

Where  $R_{ohm}$ ,  $R_{atv}$ , and  $R_{con}$  are respectively the representation for the ohmic, the activation and the concentration resistance; with  $C_{dc}$  corresponding to the membrane capacitance due to the double layer effect. The double layer effect arises when two different electrically charged materials are put in contact. Alternatively two things can happen, a concentration of charges in the contact surface or charge transference from one material to the other.

The equation that represents the voltage behavior during transients can be expressed as:

$$V(t) = V(\infty) + [V(0^+) - V(\infty)] \cdot \exp(-t/\tau) \quad (22)$$

Where  $V(\infty)$  is the final value to which the voltage will go after the load variation, and  $V(0^+)$  is the voltage initial value, before the variation of the load fed by the PEM fuel cell. The time constant ( $\tau$ ) is a measure of the necessary time for the transient analysis in RC circuits, computed by the following equation:

$$\tau = R_{th} \cdot C_{dc} [s] \quad (23)$$

and  $R_{th}$  is the Thevenin equivalent resistance of the circuit seeing from the capacitance.

### 3. Methods

In order to develop this study, computational modeling tools were built up to model the fuel cell behavior through a detailed theoretical base taking into consideration assembling and operating parameters.

With this purpose; to build the fuel cell simulator besides the operating parameters already mentioned ( $T_{op}$ ,  $I_{op}$ ,  $P_{H_2}$ ,  $P_{O_2}$ ,  $\phi_{H_2}$ ,  $\phi_{O_2}$ ,  $\lambda_{H_2}$ ,  $\lambda_{O_2}$  or  $\lambda_{Air}$ ), the constructive parameters (electronic transference coefficients, electrode reaction level constants, and the physicochemical properties of electrodes and membrane), and the dimensioning parameters for the fuel cell stack (number of cells, cell area and de membrane thickness) were also considered. The simulation results are compared with practical experiments.

The experimental tests were made through controlled processes using different models and prototypes of PEMFC fuel cell stack as the system shown in the basic scheme of Figure 2.

Under normal operation a frequency inverter is used to feed *ac* energy due to the voltage regulation showed by the fuel cell. An electronically controlled resistive load was used in order to make possible a better control of the necessary electrical load during laboratory experiments.

### 4. Results

#### A.. PEM fuel cell in steady-state load regimen

Figure 3 shows the behavior of a cell with net area of  $5\text{cm}^2$ , fed by hydrogen and pure oxygen with feeding pressures of 1 atm, stoichiometries of 1.1, humidification 100% under operating temperatures of  $40^\circ\text{C}$ ,  $60^\circ\text{C}$  and  $80^\circ\text{C}$  in static load regimen, being the curves assembled from the cell voltage response according to the current requested by the load. Similar curves can be obtained fixing the temperature and changing other operating parameters.

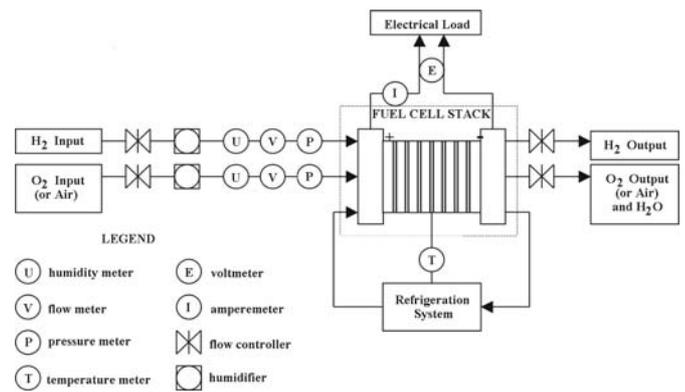


Fig. 2. Typical elemental operating scheme for a PEM fuel cell stack.

Table II – Design characteristics for the first prototype

Description	Symbol	Amount
Area of the cell	$A_{cel}$	$5\text{ cm}^2$
Number of cells	$N_{cel}$	1
Membrane	-	Nafion® 112
Electronic transfer coefficient (cathode)	$\alpha_c$	0.43
Electronic transfer coefficient (anode)	$\alpha_a$	1.0
Reaction grade constant (cathode)	$k_c^\beta$	$2.7\text{ cm/s}$

Figure 3 shows the behavior of the cell with the variation of temperature for the first prototype with constants described in Table II:

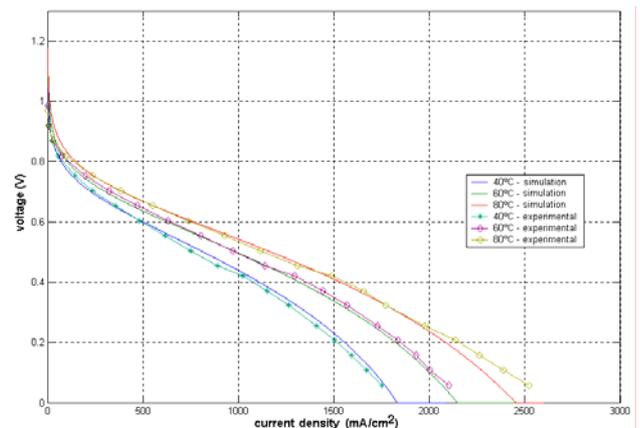


Fig. 3. Behavior of a PEM fuel cell under static load with the temperature.

Figure 4 shows the behavior of the cell with the variation of pressure for the second prototype with constants described in Table III:

Table III – Design characteristics for the second prototype

Description	Symbol	Amount
Area of the cell	$A_{cel}$	$20\text{ cm}^2$
Number of cells	$N_{cel}$	1
Membrane	-	Nafion® 112
Electronic transfer coefficient (cathode)	$\alpha_c$	0.43
Electronic transfer coefficient (anode)	$\alpha_a$	1.0
Reaction grade constant (cathode)	$k_c^\beta$	$3.5\text{ cm/s}$

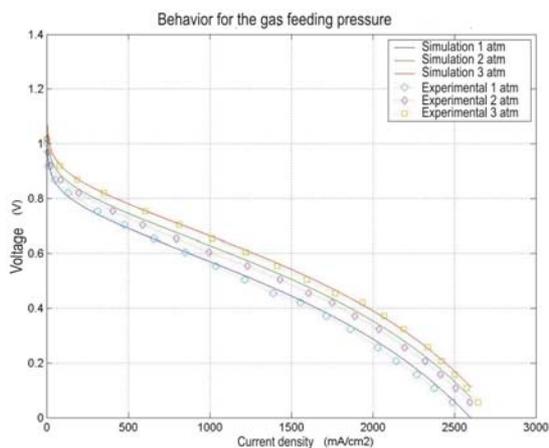


Fig. 4. Behavior of a PEM fuel cell under static load with the gas pressure.

The third prototype was used for experimental and dynamic simulation tests, it is a fuel cell stack built from two cells, assembled in a test bench with main design characteristics as shown Table IV.

Table IV – Design characteristics for the third prototype

Description	Symbol	Amount
Area of the cell	$A_{cel}$	80 cm <sup>2</sup>
Number of cells	$N_{cel}$	2
Membrane	-	Nafion® 112
Electronic transfer coefficient (cathode)	$\alpha_c$	0.43
Electronic transfer coefficient (anode)	$\alpha_a$	1.0
Reaction grade constant (cathode)	$k_c^0$	1.3 cm/s

### B. Utilization of air instead of pure oxygen

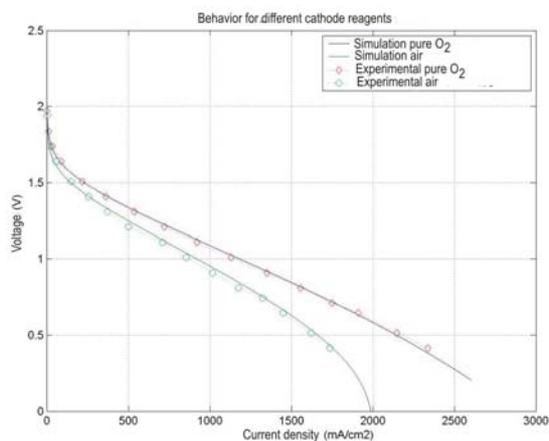


Fig. 5 – Behavior of a PEM Fuel Cell for pure oxygen and air.

For this analysis it was used the second prototype with air or oxygen as a cathode reagent with an operating temperature of 50° C. The other cell parameters are the ones specified in Table II. The values obtained experimentally and through computational simulation are indicated in Figure 5.

The result above shows the developed model efficiency and the success in the collection of constructive parameters, and also demonstrates the influence of the use of atmospheric air and pure oxygen.

Practically, this substitution, although showing loss of efficiency, it is advantageous for commercial projects, avoiding the need of oxygen transport and storage, since one of the major challenges for the PEM fuel cells is to find an efficient way to store bulky amounts of gaseous fuels like hydrogen and oxygen.

The decreasing efficiency is due to the lower oxygen concentration in the composition of atmospheric air, and to the consequent increase in the cathode concentration effect (Figure 6). The ohmic voltage drop and activation effect are not dependent on this parameter.

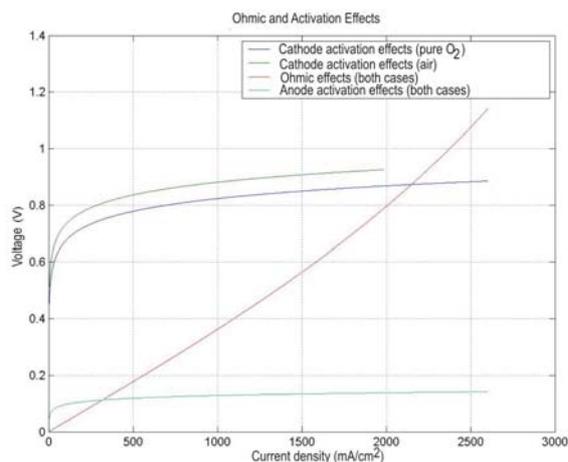


Fig. 6 – Ohmic and activation losses when comparing feeding of pure oxygen and air.

A second reason for this variation is the concentration effect in the cathode. With the decrease in concentration of the fuel gas, the maximum possible current in this electrode decreases. Adding the fact that the experiment has been made in a temperature relatively low (50°C), bring the cell response curve for high current densities close to the saturation limit (oxygen concentration in the interface membrane-electrode close to zero). This phenomenon occurs in a region where the power is decreasing, and could still be possible the use of the cell stack in this operating condition.

Figure 7 shows also that the anode concentration effect is minimal, and due to its very small amount, they are irrelevant to the process.

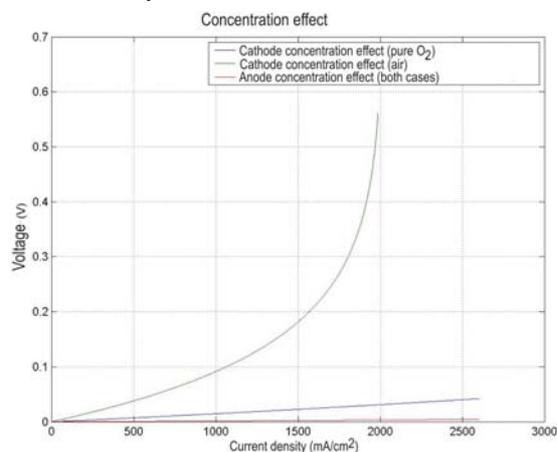


Fig. 7. Concentration effects when comparing feeding of pure oxygen and air.

### C) PEMFC in dynamic load regimen[4]

In Figures 8, 9, 10 and 11 it is shown the simulation of the behavior of a fuel stack of two PEM fuel cells with data given in Table III and operating under a temperature of 70°C fed by hydrogen and pure oxygen with pressures of 1 atm, stoichiometries of 1.1 and humidification 100%, where was imposed a current pulse from a load that changes from 45A to 80A over a 5 seconds interval (dynamic load variation). Similar studies were done taking into consideration several operating configurations.

All the obtained results in practical experiments were compared with the corresponding computer simulation.

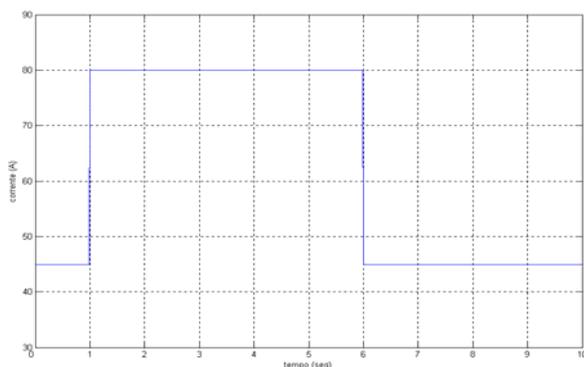


Fig. 8. Graph of imposed current (A) against time (s)

## 5. Discussion

The mathematical simulation reproduced accurately the behavior of the PEM fuel cells evaluated. The biggest difficult by far was the determination of constructive parameters for the materials used in the assembling of the cells. This happened due to the fact that the technology employed in this cells is still under development. Some materials were adopted from other industrial processes (like the Nafion®) and materials developed experimentally with separating plates, spreaders and electrodes. With the technological evolution of PEM fuel cells, and the development of proper, more efficient and standardized materials those difficulties will be reduced considerably.

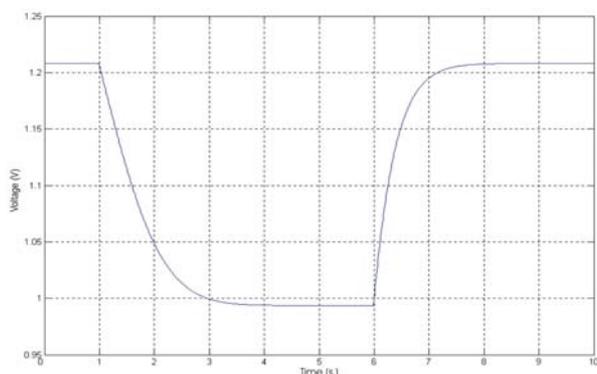


Fig. 9. Graph of voltage (V) against time (s).

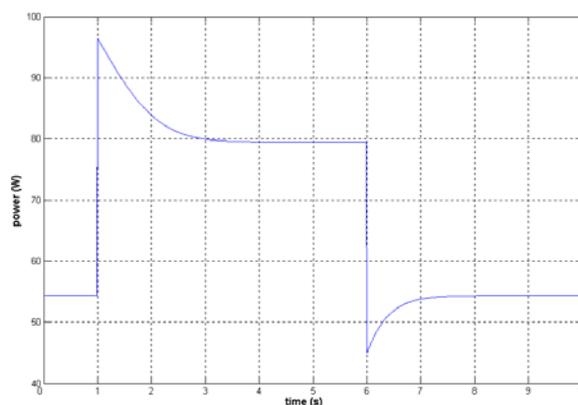


Fig. 10. Graph of power (W) against time (s).

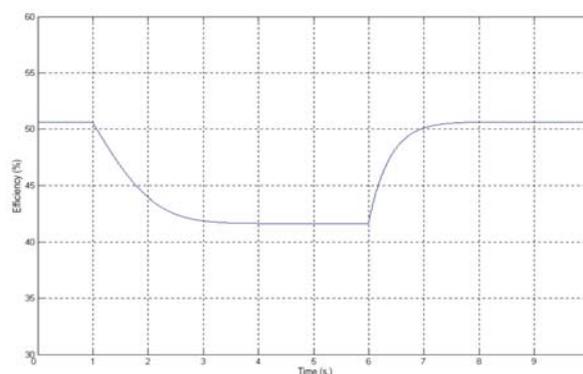


Fig. 11. Curve of efficiency (%) against time (s).

The PEM fuel cells are sensible to all operational parameters. In the case of pressure values and flow of gases fed, the effect was more expressive when the variations lead to critical situations of activation or concentration of gases in the electrodes.

In the case of values of humidification of feeding gases, the effect was more expressive when the variations took to critical situations of polymeric membrane dryness.

The effect of operating temperature variation is felt all over the process, being also the one that is more difficult to control. All the energy produced by the reaction and not converted into electrical energy is dissipated as heat, so the cooling system must be very efficient in case of large fuel stacks.

## 6. Conclusion

Mathematical simulation is a useful tool, allowing the reproduction with good degree of fidelity the PEM fuel cell behavior. Should be mentioned here the fact that many of the assembling parameters used were not easy to be obtained without the help of the prototype in the laboratory.

The PEM fuel cells under scrutiny showed their enormous potential producing electrical energy with an impressive efficiency, between 40% and 60%, when compared for example, with internal combustion engines. The byproducts of the whole energy generation process are oxygen and hot water. It is also possible the use of the generated hot water in domestic and industrial processes.

However it is not possible to use the water in co-generation processes due to the relatively low temperature (up to 90°C). The studies of static and dynamic behavior under variable loads showed the large influence of variable operating parameters in the performance of the cell. Due to this aspect it is necessary a rigid control system for this variables in order to improve the performance of the PEM fuel cell stack.

As can be seen from this study, the coupling of a fuel cell with an inverter to produce *ac* current is not as simple as it seems. The fuel cell changes its parameters for each load or operating point. The inverter design is not simple since its characteristics should be in agreement with the fuel cell variable parameters.

The study of the dynamic behavior shows that the RC constant during the load increase is bigger than during the load decrease, as can be seen in Figure 9; opposing to the fact that the resistance increases with the value of current and temperature, this happening due to the decrease of holes and free electrons in the electrodes. This fact shows the influence of parameters related to the feeding of gases in the final value of the cell RC constant. The implementation of the fuel cell needs a very sophisticated set of controls to operate in a variable load condition.

The implementation of this model allows the assembling of polymeric membrane hydrogen stacks of different sizes, and also allows the increase on the knowledge of effects of variations on the components over the performance in each of the cells.

Anode concentration and activation effect proved to be less dependent of the type of feeding (air or pure O<sub>2</sub>) than the cathode effects. Ohmic voltage drops have a non-linear dependency with current and can be smaller than the anode activation losses for operating current densities.

The developed computational simulator, demonstrated to be an efficient and valuable tool to the development of polymeric membrane fuel cell stacks; making possible the verification of planned effects without the need of the extra design cost of assembling a new prototype.

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