STUDY OF THE PERFORMANCE OF A POLYMER ELECTRODE FUEL CELL

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Abstract. *This work reports the performance of a proton exchange membrane fuel cell, with the objective of reaching a set of reference conditions to be used for further testing of other types of fuel cells using similar geometrical configurations.*
The fuel cell tested has an active membrane area of 25 cm^2 and different serpentine configurations for the anode and cathode gas flow channels. DuPont membranes reference H25-bMEA5 with a NAFION layer of 25 µm thickness were used. The cell was tested in a laboratory scale test rig, by feeding pure hydrogen to the anode and air to the cathode. Experiments were carried out for different combinations of operating temperatures of the gas flows, of the cell operation, and also for different degrees of humidification of the hydrogen and air flows.
Experimental data are shown as plots of polarization curves of the cell and possible explanations for the obtained results are discussed. Increasing the operating temperature of the cell improved its performance, provided that the humidification of the flow of feeding gases was adequate. The best performance of the cell was detected when operating it at 60 ºC and for the humidification temperatures of 80 ºC and 70 ºC, respectively for hydrogen and air. The humidification of both gas flows leads to the best performance when compared to the humidification of a single gas flow.
A reasonable performance can be achieved without humidification of gas flows provided a careful choice of air flow and cell temperature operating is reached.

Keywords*: fuel cells, hydrogen, proton exchange, polymer membranes*

1. INTRODUCTION

Proton exchange fuel cells or polymer electrolyte membrane fuel cells PEMFC have this particular name owing to the special polymeric membrane used as electrolyte (Springer et al., 1991; Appleby and Foulkes, 2000; Cappadonia et al, 2000). The most common used fuel is pure hydrogen (Kordesch and Simader, 1996). Other fuels, which must be previously converted to hydrogen like for example methanol, ethanol or methane (Cappadonia et al, 2000) are also used. Variations of this basic approach are direct methanol fuel cells DMFC and direct formic acid fuel cells, DFAFC (Hirschenhofer et al, 1998; Rice et al., 2002; Larminie and Dicks, 2004; Dunn-Rankin et al., 2005). The most common membrane used in PEMFC's is composed by NAFION a trade mark from Dupont, which when conveniently humidified allows proton conduction from the anode to the cathode. Due to the need of membrane humidification operation temperatures are relatively low, below 100 ºC, even working under high pressure, Hoogers (2003). Low operating temperatures requires the use of catalysts to increase the reaction rate; the most common catalyst are platinum based and are highly sensitive to CO poisoning although they tolerate CO_2 (Joon, 1998).

The single liquid product of this type of cell is water and because of this the polymer electrolyte membrane fuel cells have no corrosion problems, are easily built and can work with high current densities and when used a liquid fuel like methanol or formic acid, the fuel handling, storage and transportation problems are reduced (Hirschenhofer et al, 1998; Rice et al., 2002; Dunn-Rankin et al., 2005).

There are many results published about this type of fuel cells through experiments carried out all over the world (Nguyen and White, 1993; Mosdale et al., 1996; Barbir and Gómez,1997; Sridhar et al., 2001; You and Liu, 2002; Evans, 2003; Wang et al., 2003; Ge and Yi, 2003; Larminie and Dicks, 2004; Wang and Hongtan, 2004, Steidel et al., 2004;), but many of the available data refer to cells bought at suppliers external to the research team.

In the present work the objective was to evaluate the operating performances of a fuel cell of a given configuration to act as a reference for a set of equivalent size cells working with different fuels, namely methanol, ethanol and formic acid. The present cell is the simplest as the fuel is the hydrogen, but is leading the way for a future comparative assessment among all the configurations.

The performance of a fuel cell is influenced by many parameters, such as operating temperature, humidification of the gas streams, gas flow rate and gas pressure. It is necessary to know how such parameters affect the performance of the fuel cell.

The humidification of the fuel cell is essential for to obtain a good performance. The polymer membrane in the PEMFC must have the adequate humidification to facilitate proton transport. It must have enough water so that it does

not either becomes dehydrated and or flooded with water, both events leading to the inhibition the electrochemical reactions. In practice, humidification of the anode fuels and/or cathode oxidants is often used to provide sufficient membrane hydration (You and Liu, 2002).

There are three mechanisms that dominate the phenomenon of water management inside the cells: convective transport due to pressure gradients in the cell, diffusive transport due to a counter gradient (back diffusion), and electro-osmotic drag due to protons migrating from the anode to the cathode. But the balance between electro-osmotic drag and back diffusion is the key to determining membrane hydration (Evans, 2003).

The operating temperature of the fuel cell has influence too in the performance. Usually the increase of the operating temperature has good results, until a limit operating temperature for the membrane is reached. Above of this limit the damage of the membrane can occur. More recent research data refer new developments towards higher membrane temperatures (Zhang et al. 2006), up to 130-140 ºC. According to Atlins et al. (2003), the humidification temperature of the gas flows must be above or equal to the operating temperature, in way to assure that the cell is well hydrated.

Pure hydrogen was used on the anode side and air was used in the cathode side. Polarization curves for the cell operating at different temperatures and humidification temperatures for the hydrogen and the air are presented and discussed.

2. CHARACTERISTICS OF THE FUEL CELL

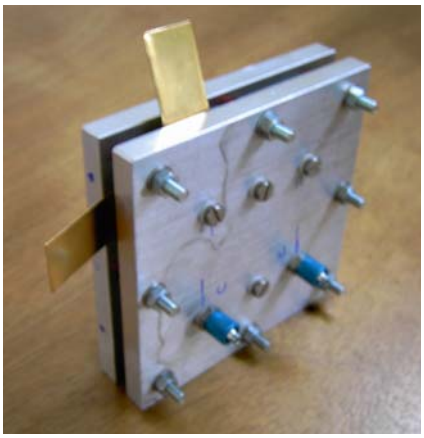

Figure 1. Fuel cell.

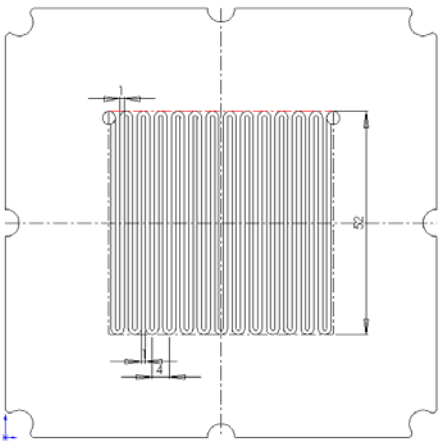

Figure 2. Carbon plates of the fuel cell.

The tested fuel cell, shown in Fig. (1), was designed and build at INEGI with the exception of the MEA (MEA - membrane electrode assembly) which was purchased from Dupont Fuel Cells. The fuel cell has an active membrane area of 25 cm^2, and the overall configuration for the anode and cathode side serpentine flow channels, is represented in figure 2. The depth of the channels is of 0.7 mm in the anode and 1.5 mm in the cathode.

The membrane reference is H25-bMEA5 with a NAFION layer of 25 µm thickness. Gaskets to ensure proper joining among the different plates were also supplied by Dupont.

Details on the construction of the fuel cell can be seen at Guimarães et al. (2006).

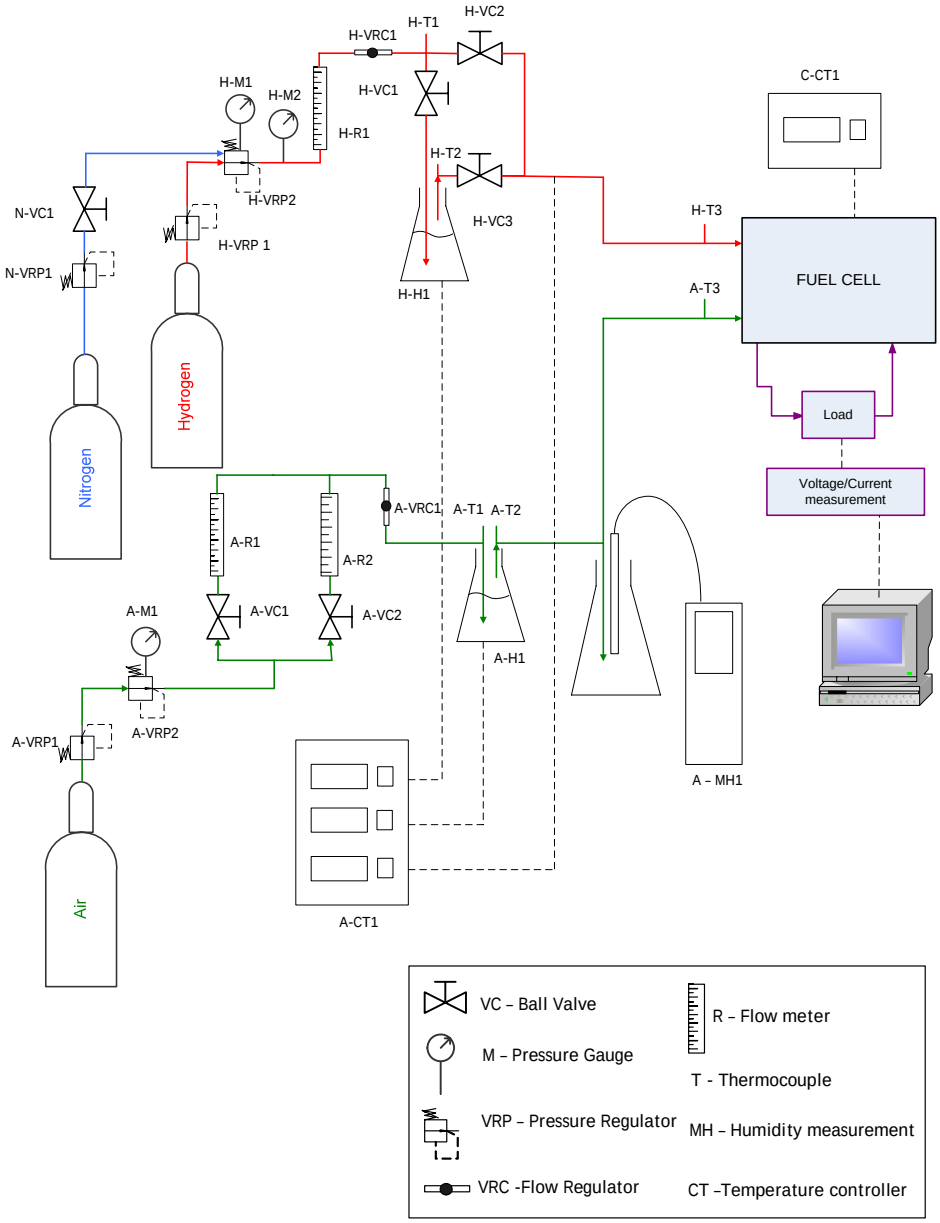

Figure 3. Schematic layout of the experimental setup.

3. EXPERIMENTAL SET-UP AND PROCEDURE

The experimental setup used for the testing of the fuel cell is schematically represented in Fig. (3). Feeding gases came from gas cylinders and their flows were measured through KDG-Mobrey rotameters. For the air flow two rotameters were used, a KDG-Mobrey 2-D-150 B2S for air flow in the range of 0.6 to 4.6 l/min and other, reference 6-A-150 B6G, for the air flow range of 3 to 15 l/min, both ranges measured at 1 atm gauge and 30 ºC. For hydrogen flow measurement a rotameter, also from KDG-Mobrey ref 1.6-A-150 S, was used for the gas flow range of 0.8 to 1 l/min at 0.4 atm gauge and 30 ºC. During testing, two types of gas feeding situations were considered, flow source and pressure source. In the first instance the hydrogen flow is kept constant during the experiment and the output hydrogen flow from the cell should also be measured to account for the fuel consumption; in the second instance the hydrogen feeding is being kept at constant pressure and no hydrogen output flow is allowed from the cell. To account for the hydrogen output during the flow source experiments, two soap bubble meters were used, one with three volume ranges of 1, 10 and 500 ml and other with a single graduated range of up to 25 ml. The data presented and discussed in this work refer only to experiments carried out with flow source feeding of hydrogen.

For the humidification of the air and hydrogen flows, bubbling of the gases through deionized water inside Erlenmeyer flasks was adopted. To control the humidification temperature each Erlenmeyer flask was thermally isolated and surrounded with an electrical resistance (50 W/m) activated by a Osaka OK 31 digital temperature

controller. The same procedure was applied along the connecting pipes from the humidification point up to the entrance of the fuel cells to guarantee the temperature stabilization of each reacting gas flow, as well as to control the operating temperature of the fuel cell.

For the measurement and control of the cell electrical output it was used an electric load reference LD300 300W DC Electronic Load from TTI. This device could work with five different operating modes:

- Constant current – two possibilities were available, 0 to 8 A (with 1 mA resolution) and 0 to 80 A (10 mA resolution), with a precision of ±0.2 %+20 mA;
- Constant tension – two possibilities were available, Vmin up to 8 V (1 mA resolution) and Vmin up to 80 V (10 mA resolution (were V min is 10 mV for low power situation and 2 V for 80 A). Precision is ±0.2 %+2 digits;
- Constant power – the available power range goes from 0 till 320 W, with a precision of 0.5 %+2 W;
- Constant conductance - operating range from 0.01 up to 1 A/V (1 A/V resolution) and from 0.2 up to 40 A/V (resolution of 0.01 A/V) with a precision of 0.5 %+2 digits;
- Constant resistance – operating range from 0.04 up to 10 Ω (0.01 Ω resolution) and from 2 to 40 Ω (with 0.1 Ω resolution) with a precision of 0.5 %+2 digits.

This load was connected to a data acquisition system composed by Advantech boards installed in a desktop computer. The used data acquisition software was GENIE version 2.12.

4. EXPERIMENTAL RESULTS

The experimental results referred herein present the performance of the fuel cell at several different operating conditions, through the combination of four cell operating temperatures, 20, 40, 60 and 80 ºC, four humidification temperatures for the hydrogen flow, 20, 40, 60 and 80 ºC, and four humidification temperatures for the air flow, 20, 40, 60 and 70 ºC.

4.1. Humidification of the hydrogen flow

Table 1 – Performance of fuel cell with hydrogen humidification.

T humd H_2 (ºC) / **T cell (ºC)**	20	40	60	80
20	7.20 W 12.56 A	7.28 W 12.50 A	7.43W 12.50 A	7.88 W 13.00 A
40	5.04 W 10.50 A	7.51 W 12.79 A	7.12 W 12.00 A	7.7 W 13.00 A
60	-----	-----	4.20 W 9.60 A	7.47 W 12.60 A
80	-----	-----	-----	3.59 W 8.50 A

This first set of data concerns the influence of the temperature of humidification of the hydrogen flow on the performance of fuel cell. Table (1) has the overall results whereas Figs. (4) and (5) present the polarization curves for the cell operating at 40 ºC and 60 ºC.

At a cell operating temperature of 20 ºC its performance is similar for all hydrogen humidification temperatures, Tab. (1). As the cell operating temperature rises it is realized that higher hydrogen humidification temperatures result in better cell performance. This is quite clear from the analysis of Tab. (1), as cell temperature increases the number possible operating conditions decreases and at an operating temperature of 80 ºC the cell only works provided the hydrogen humidification temperature is equally high. For any cell operating temperature the best performance is always achieved with the hydrogen humidification temperature of 80 ºC.

Considering the overall behavior of the fuel cell which can be deduced from the analysis of Tab. (1), it is observed a better performance of the fuel cell for a given value of the corresponding operating temperature, the higher is the humidification temperature of the hydrogen flow. This is because the warmer is the hydrogen flow the more elevated is its capacity to carry moisture, leading to better humidification of the membrane. At lower cell operating temperatures, the hydrogen flow saturates with water sooner and consequently the positive effect of this action is more important. For higher cell operating temperatures, the situation is the opposite, it is more difficult to take the hydrogen flow close to saturation conditions, thus it enters the cell in a dryer condition and the membrane does not become as well humidified as before. The cell performance will be only adequate for the highest humidification temperatures.

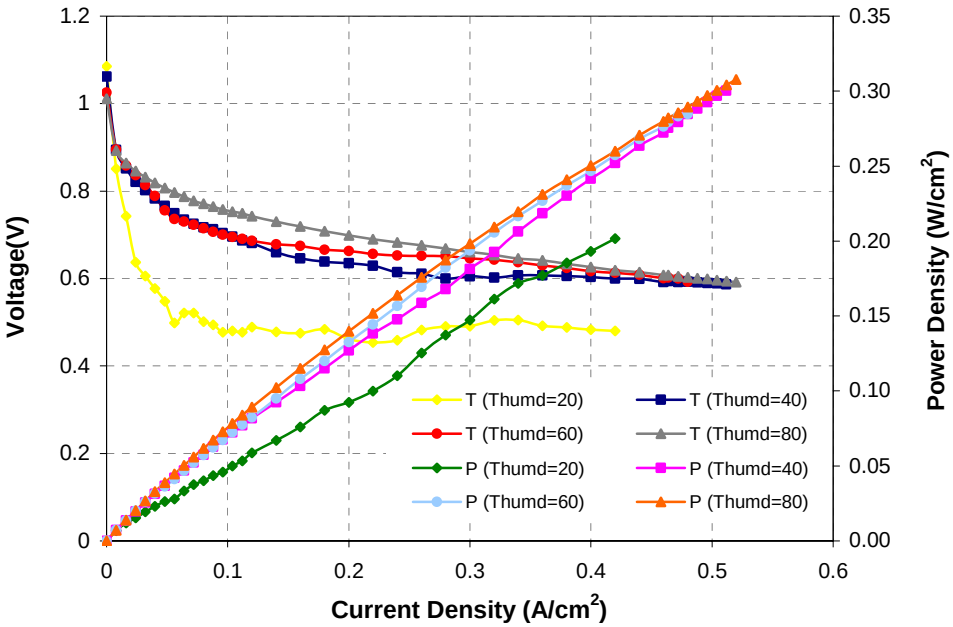

Figure 4. Polarization curves for fuel cell at the operating temperature of 40 ºC.

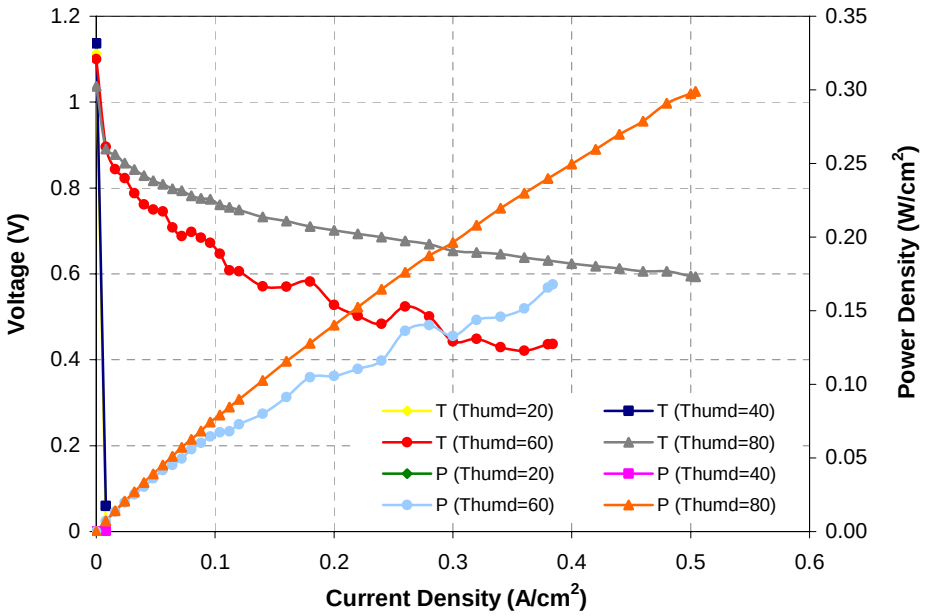

Figure 5. Polarization curves for fuel cell at the operating temperature of 60 ºC.

For the same reason, for a given humidification temperature, a higher cell operating temperature leads to lower cell performance. It is known that at lower temperatures the oxygen reduction needs a higher voltage drop to produce the same current intensity, but on the other end the membrane resistance is lower at lower temperatures (You and Lui, 2001) and water activity is then higher. As the cell performance is better at lower temperatures, or at least the cell is more forgiving towards lower hydrogen humidification temperatures, it can be concluded that the importance of proper membrane humidification exceeds the losses associated to the voltage drop. The influence of the humidification temperature is stronger for low current densities, a situation were the membrane is never fully hydrated. As current densities raise, the water production rate in the cathode increases and the electro-osmosis water displacement humidifies the membrane reducing the weight of the external humidification procedure.

When the external humidification of the hydrogen flow is not enough, the cell performance oscillates because of the lack of uniformity of water distribution inside the membrane.

Finally, looking at the plotted polarization curves it can be observed that the cell has no concentration polarization region because the amount of supplied hydrogen and air are well above the minimum required rates, i.e. there are no mass transfer resistances.

4.2. Humidification of the air flow

For this second set of tests four operating temperatures (20, 40, 60 and 80 ºC) and four air flow humidification temperatures were chosen (20, 40, 60 and 70 ºC). The choice of the maximum temperature of air humidification was limited by the available heating power. Table (2) presents the overall results for the performance of cell for this situation of the humidification of the air flow.

Table 2 – Performance of fuel cell with air humidification.

T humd Air (ºC) / T cell (ºC)	20	40	60	80
20	6.69 W 11.88 A	7.10 W 12.12 A	7.10 W 11.94 A	6.55 W 11.31 A
40	6.08 W 10.87 A	5.92 W 10.45 A	6.15 W 11.13 A	5.93 W 9.7 A
60	0.17 W 0.55 A	1.04 W 3.0 A	5.63 W 9.47 A	5.11 W 8.87 A
80	-----	0.18 W 0.57 A	0.59 W 1.92 A	1.52 W 4.93 A

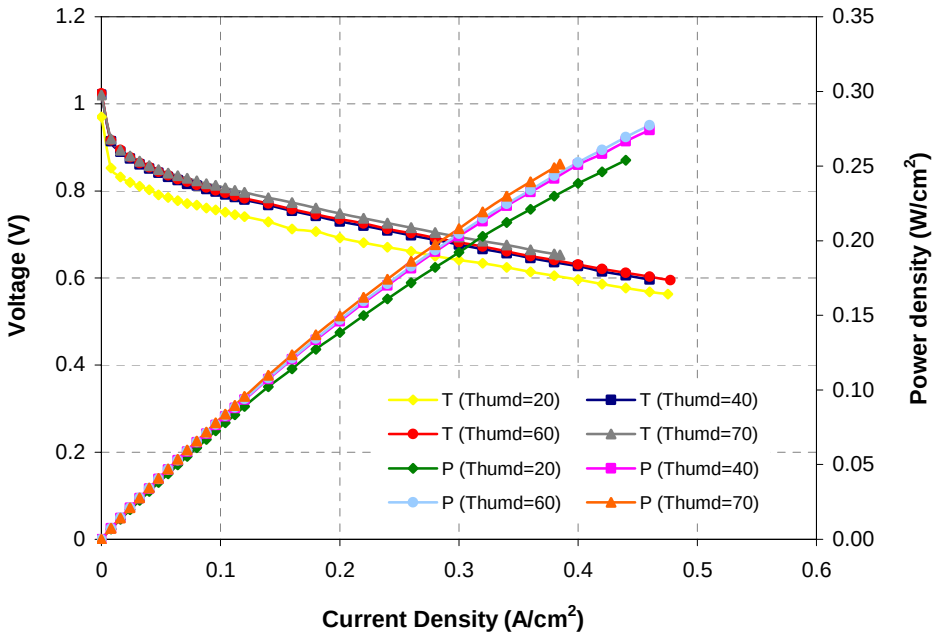

Figure 6. Polarization curves for fuel cell at the operating temperature of 20 ºC.

Fig. (6) presents the polarization curves for fuel cell operating at 20 ºC and four different air flow humidification temperatures, while Fig. (7) presents the equivalent polarization curves but for the fuel cell operating at 80 ºC.

From the observation of both figures, Fig. (6) and Fig. (7), as well as from Tab. (2), it is evident the better performance of the cell for higher air humidification temperature, while the increase of operating temperature has an opposite effect.

The better cell performance with the increase of air humidification temperature leads to higher relative humidity of the incoming air flow, enhancing the humidification of the membrane, but if the cell operating temperature raises the relative humidity of this air flow diminishes and the membrane humidification becomes less efficient.

Similarly to what was observed through the humidification of the incoming hydrogen flow, the influence of the humidification temperature of the air flow for low current intensity is stronger when the water release rate is still low and membrane humidification is not perfect, but as the water release rate increases the membrane humidification augments and the weight of influence of external air humidification upon cell performance diminishes.

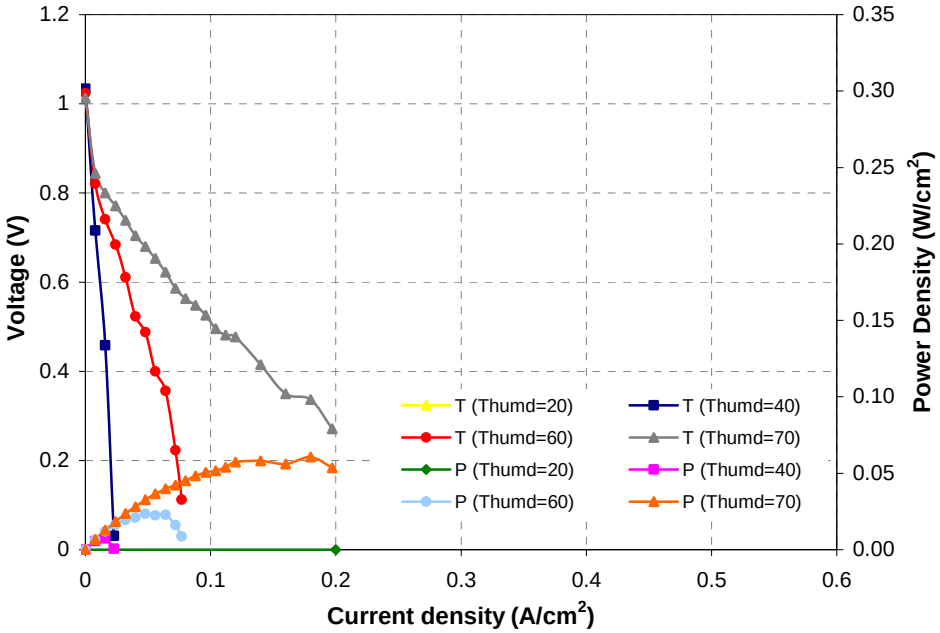

Figure 7. Polarization curves for fuel cell at the operating temperature of 80 ºC.

4.3. Humidification of the hidrogen and air flows

This third set of tests was carried out with four cell operating temperatures (20, 40, 60 and 80 ºC) and four hydrogen and air flow humidification temperatures (20, 40, 60 and 80/70 ºC respectively). Table (3) presents the overall results for the performance of cell for this situation of the humidification of the both gases flow.

Figure (8) and Fig. (9) present the polarization curves for humidification temperature of the both gases of 20 ºC and 80 ºC respectively ,and for four different fuel cell operating temperatures.

Through the analysis of Table 3, it is again observed a better performance of the cell with the increase of the humidification temperature of both gas flows. Comparing the results presented in all tables, Tab (1), (2) and (3), it is verified that the humidification of the both gas flows inhibits the fast drying of the membrane. With the humidification of the both gas flows, a better cell performance is obtained when compared with the humidification of any single gas flow.

Table 3 – Performance of fuel cell with hydrogen and air humidification.

T humd H2/Air (ºC) / **T cell(ºC)**	20	40	60	80/70
20	5.98 W 9.51 A	6.35 W 9.72 A	6.41 W 9.92 A	6.86 W 10.3 A
40	5.29 W 9.68 A	6.63 W 10.17 A	6.77 W 10.43 A	6.85 W 10.23 A
60	0.26 W 1.50 A	2.87 W 6.56 A	6.18 W 10.00 A	7.15 W 10.80 W
80	-----	0.98 W 1.80 A	2.72 W 6.00 A	5.41 W 9.07 A

For the same temperature of humidification, the performance of the fuel cell increases with the increase of the operating temperatures, but only if the humidification is enough. This generally happens when the humidification temperature is 20 ºC above the fuel cell temperature, Fig. (10). On the contrary, when the humidification temperature is 20 ºC below the fuel cell temperature, the performance of the cell suffers a huge decrease, Fig.(11).

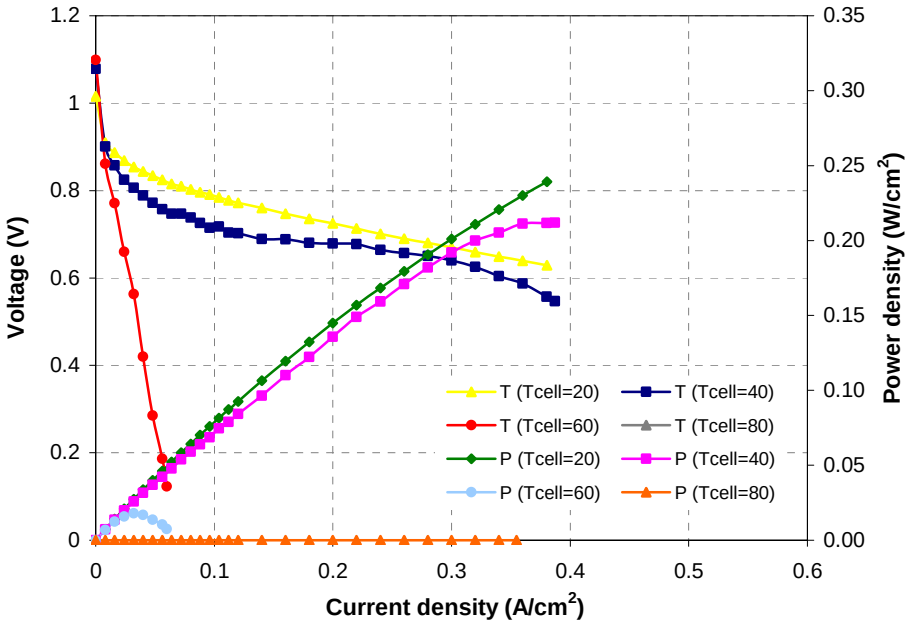

Figure 8. Polarization curves for fuel cell at the humidification temperature of the hydrogen and air of 20 ºC.

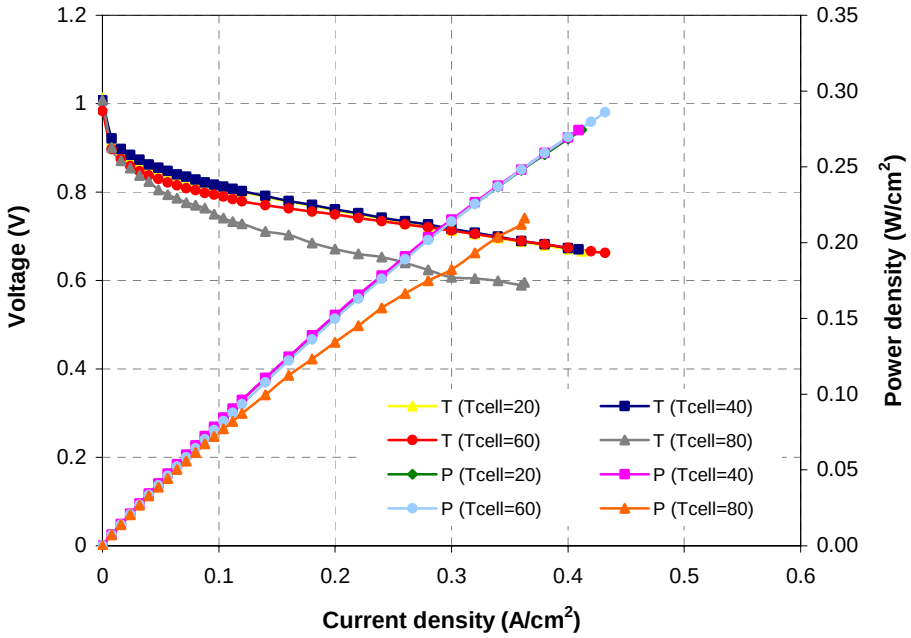

Figure 9. Polarization curves for fuel cell at the humidification temperature of the hydrogen and air of 80 ºC.

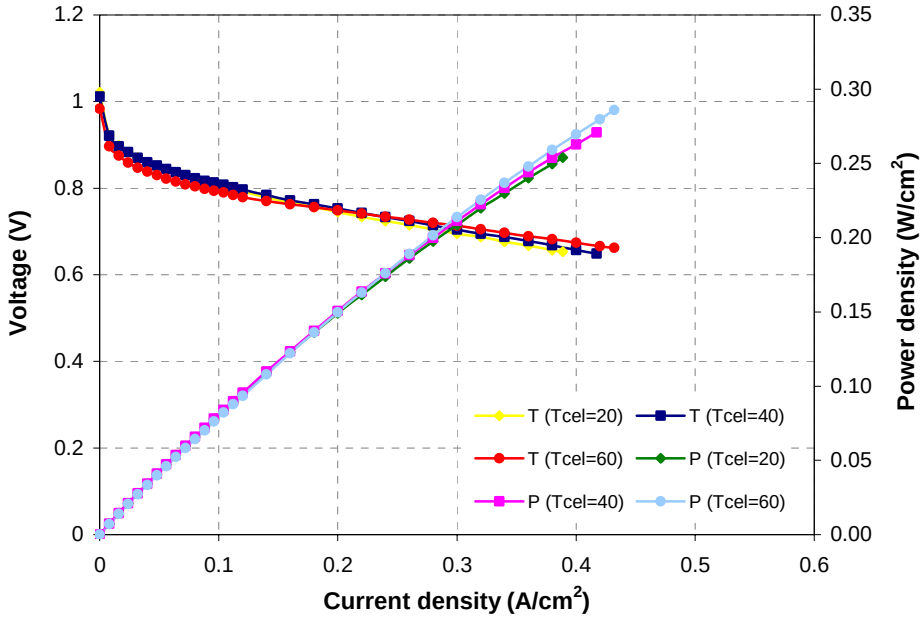

Figure 10. Polarization curves for fuel cell when the humidification temperature is 20 ºC above the fuel cell temperature.

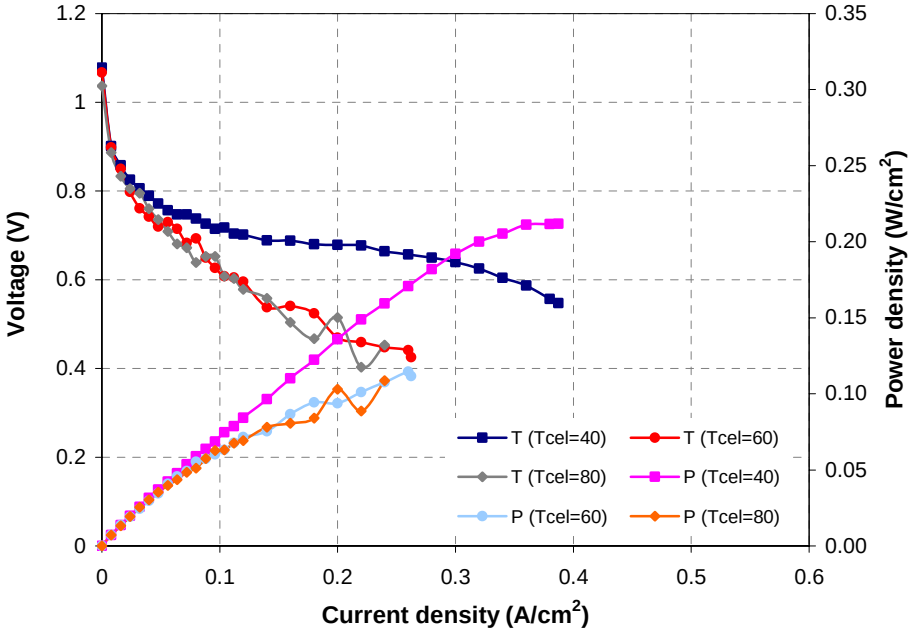

Figure 11. Polarization curves for fuel cell when the humidification temperature is 20 ºC below the fuel cell temperature.

4.4. Absence of humidification of the gas flows

If the cell is operating without humidification of the gases it still can perform well if there is a proper adjustment between the flow of the gases and the cell operation temperature. In Fig (12) are presented the polarization curves of the cell operating at different temperatures, without humidification of the gases and for an air flow of 3 l/min.

Through the analysis of Fig 3, it is verified that operating the cell at 20ºC and using an air flow of 3l/min, there is a reasonable performance. It is then possible to work the fuel cell without humidification of the gases provided an optimum operating setup is found.

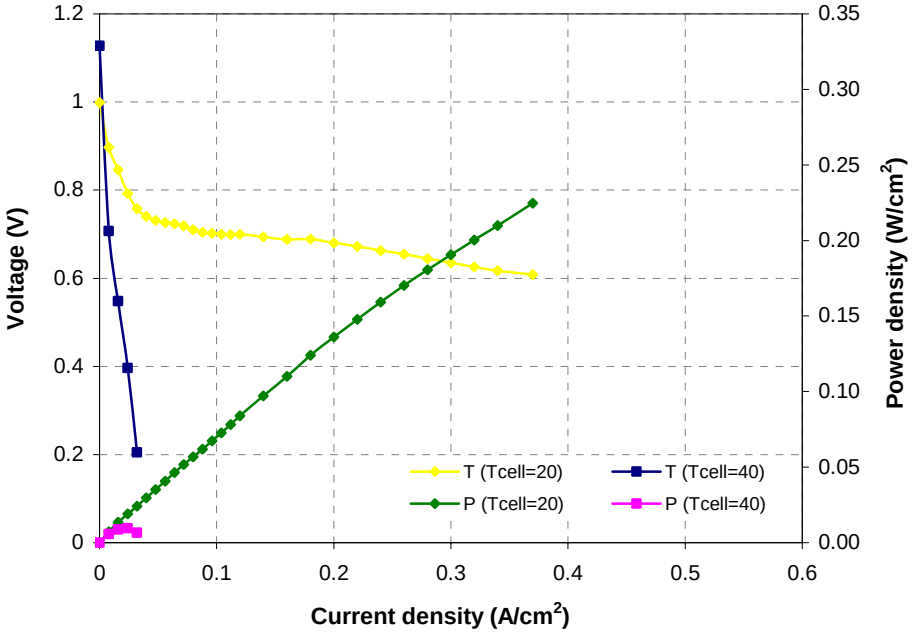

Figure 12. Polarization curves for fuel cell without humidification of the gases.

5. CONCLUSIONS

Results on the analysis of the performance of a polymer electrolyte membrane fuel cell with different humidification degrees of the hydrogen and air flows were presented and discussed. From such results the conclusion is that with the humidification of both gas flows better results are obtained, when compared with humidification of a single gas flow. For low current densities air humidification is more important than hydrogen humidification, while at high current densities the humidification of hydrogen induces a better cell performance.

In the present analysis, where the humidification of a single gas flow was accounted for, it was found that for a given humidification temperature of the gas flow, be it hydrogen or air, cell performance degrades with the increase of its operating temperature and the higher this operating temperature, the higher the performance degradation.

As a general rule it was also found that whatever is the cell operating temperature, in the tested temperature range of 20 to 80 ºC, the better cell performance is obtained with the higher gas humidification temperature.

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