FABRICATION AND EVALUATION OF ELECTRODES FOR POLYMER ELECTROLYTE FUEL CELLS

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ABSTRACT

In this work, the development and results on the electrochemical studies of low catalyst loading gas diffusion electrodes for polymer electrolyte fuel cells are reported. The single cell data were analyzed employing the current knowledge derived from theoretical models of the electrode structure and of the fuel cell system.

INTRODUCTION

Recent developments in polymer electrolyte fuel cells (PEFC) led to a growing interest in this system, particularly for transportation applications. Perhaps the major breakthrough accomplished lately on this fuel is the improvement on the design, composition and loading of platinum in the gas diffusion electrodes (1-3).

This work reports single results obtained with low catalyst loading gas diffusion electrodes developed on the basis of the concept proposed by Gottesfeld and co-workers (3), combined with the standard approach of Srinivasan and co-workers (2). Studies on these electrodes involve the effect on the fuel cell operation of the structure and composition of the diffusion and catalyst layers on the electrodes and the effects of the membrane thickness, cell temperature and reactant pressure.

EXPERIMENTAL

The electrodes were prepared by a combined filtration/brushing procedure using carbon supported catalysts (E-Tek Inc.), carbon powder (Vulcan XC-72, Cabot), a carbon cloth substrate (PWB-3, Stackpole), a polytetrafluoroethylene (PTFE) suspension (Teflon T-30, DuPont), and a Nafion® solution (5 wt.%, Aldrich). PTFE and carbon powder were used to prepare the diffusion layer which was deposited on both sides of the carbon cloth by filtration. The catalyst layer was made by brushing an ink formed with the supported catalyst and the Nafion® solution in isopropanol. Membrane and electrode assemblies
were prepared by hot pressing the electrodes onto a purified Nafion® membrane. The electrodes were prepared with different thicknesses and PTFE contents in the diffusion layer and with varying Nafion® and catalyst loadings in the catalyst layer. Employed catalysts were 10, 20, 30, 40, 60 and 80 wt.% Pt/C and 20 wt.% Pt alloy/C (50 atom% of Pt-Cr, Pt-V, and Pt-Co).

In this work the thickness of the diffusion layer is expressed in terms of the thicknesses of the PTFE/C layers applied to the carbon cloth, which were measured from separate films deposited on a filter paper. The PTFE contents are expressed in terms of the weight percentage of PTFE to the total weight of the PTFE/carbon mixture. The catalyst and Nafion® loadings are expressed in milligrams of the materials per square centimeter in the catalyst layer.

The polarization experiments were carried out under galvanostatic conditions with humidified reactants in a conventional single cell set-up with an electrode area of ca 5 cm². Cyclic voltammetries were performed at 25 °C in the same cell, with the probe electrodes supplied with nitrogen and the counter and reference (RHE) electrodes supplied with hydrogen. The scan rate was 50 mV s⁻¹. Unless otherwise stated the standard conditions for polarization measurements were: 0.4 mgPt cm⁻², H₂/O₂ 1/1 atm, Nafion 117 membrane, and 80/95/90 °C for the temperatures of cell/hydrogen humidifier/oxygen humidifier, respectively.

RESULTS AND DISCUSSION

The analysis of the experimental polarization results was made using the semi-empirical equation proposed by Srinivasan and co-workers (4,5) for the representation of the cell potential (E) versus current density (i) characteristics:

\[ E = E^o - b \log i - Ri \]  \[ E^o = E' + b \log i_o \]

where $E'$ is the reversible potential for the cell, $b$ is the Tafel slope and $i_o$ is the exchange current density of the oxygen reduction reaction (ORR) in the Pt/C catalyst, and $R$ represents the total contributions of the linear polarization components which include the charge transfer resistance of the hydrogen oxidation reaction (HOR), the resistance of the electrolyte in the cell and the linear diffusion terms due to diffusion in the gas phase and/or in the thin film (5). In the above equation it is assumed that the resistance of the electrolyte is not dependent on current density which is a good approximation for moderate values of current densities (6).
The fittings of the above equation to the experimental results were made by a nonlinear least square method using the experimental data obtained for the cell potentials above 0.8 V for which the expected Tafel slope of the ORR in the Pt/C catalyst is $2.303(RT/F)$ (7) and the diffusion limitation in the gas phase and/or in the thin film, if present, is linear (5). Only in a few cases the fittings were carried out for potentials below 0.8 V for which the Tafel slope should be $2 \times 2.303(RT/F)$ (7). Table 1 presents the calculated kinetic parameters $E^\circ$, $b$ and $R$ resulting from some of the fittings.

On the basis of the above procedure and also from the predictions of the theoretical models of the PEFC (4-6) and of the gas diffusion electrodes with respect to the ORR (8), the analysis of the polarization diagrams was made taking into account the following facts:

(i) a possible kinetic change of the ORR on the Pt/C catalyst due to the change of oxygen coverage on the platinum surface, occurring at around 0.8 V and appearing as a change in the Tafel slope of the polarization diagram from $b = 2.303(RT/F)$ for potentials above 0.8 V to $b = 2 \times 2.303(RT/F)$ for potentials below 0.8 V (6);

(ii) the existence of diffusion limitations in the gas channels in the diffusion and the catalyst layers of the electrodes, and in the thin film of the electrolyte covering the catalyst particles, leading to pseudo resistive effects at moderate current densities and the appearance of limiting currents at high current densities in the polarization diagrams (4,5,8);

(iii) the influence of the effective surface area for the electrochemical reactions on the behavior of the electrodes which usually shift the above limiting effects to higher current densities.

Fig. 1 shows the cell potential vs. current density characteristics at 80 °C for the single cell with the electrodes with 10 wt.% Pt/C presenting different thicknesses of the diffusion layer (40 % PTFE). The corresponding values of the kinetic parameters $E^\circ$, $b$ and $R$ are presented in Table I. As expected, because the catalyst layers are the same, similar values of $E^\circ$ were obtained for the different electrodes, indicating that the value of $i_0$ (eq. [2]), and thus the electrochemical active areas, are the same in all cases. The values of $b$ are somewhat higher but still close to the value for the ORR on smooth platinum ($2.303(RT/F)$) at 80 °C, indicating a very small effect of the structure of the diffusion layer of the electrodes on the polarization behavior. In the range of 65 to 35 μm, the values of $R$ slowly decrease with decreasing thickness of the diffusion layer, which is an evidence that there is a small decrease of the linear diffusion component. This can be due to a decrease of the path for the gas diffusion or to a lesser influence of flooding problems. Below 35 μm there is an increase of $R$ probably related with to problems of electrical contact between the carbon particles. From these results it is concluded that the kinetic behavior of the electrodes with respect the HOR as well as the resistance in the membrane are the same in all cases. All these trends on the behavior of $E^\circ$, $b$ and $R$ were similar for electrodes with 20 and 30 wt.% Pt/C. Thus, as a final conclusion it is observed that for all electrodes there is an optimum diffusion layer thickness, below which there are losses due...
to poor electrical contact and above which diffusion effects due to flooding can be detected.

The study of the effect of PTFE content in the diffusion layer was carried out for the 35 and 50 μm diffusion layer electrodes, in the range of PTFE content from 50 to 10%. Fig. 2 and Table I show the results obtained for the 20 wt.% Pt/C in the catalyst layer and 35 μm thickness of the diffusion layer. These results show that no additional diffusion effects are detected even for a PTFE content as low as 10%. However, it is observed from Fig. 2 that a small increase in the electrode performance occurs when the PTFE content is diminished from 50 to 10%. Most probably, this effect is due to improved water transport, and thus better humidification of the polymer electrolyte.

The polarization results and kinetic parameters obtained for the electrodes presenting different Pt/C ratios, keeping constant the catalyst loading, are presented in Fig. 3 and Table I. As in the previous cases, the values of b at potentials above 0.8 V are all close to 2.303(RT/F) at 80 °C. An exception was found for the electrode with 80 wt.% Pt/C which, due to the smaller active area, only showed the second linear region corresponding to potentials below 0.8 V. When loaded with proportional amounts of Nafion®, the values of E° are similar for 10, 20, 30 and 40 wt.% Pt/C, indicating that the active areas are essentially the same for all these electrodes; with 60 wt.% Pt/C there is a decrease in E°, indicating a decrease in the active area. Finally, with 80 wt.% Pt/C the corresponding value of E° could not be obtained because the active area is so small that there were not enough experimental data to carry out the fitting for cell potentials above 0.8 V. The values of R for 10 to 40 wt.% Pt/C are practically constant, indicating that the membrane resistance and the HOR polarization are the major factors contributing to the values of the linear polarization term. For higher Pt/C weight ratios there is an increase of the values of R, most probably due to an increase of the linear diffusion component as a consequence of the decrease of the electrochemical active area. The increasing tendency to reach limiting diffusional currents observed in Fig. 3 for the electrodes with 60 wt.% Pt/C provide further evidence for this explanation.

The study of the effect of Nation® loading in the catalyst layer was conducted for electrodes with 10, 20 and 30 wt.% Pt/C, for amounts of Nafion® ranging from 0.4 to 2.6 mg cm⁻². Fig. 3 presents the polarization results for the electrode with 10 wt.% Pt/C loaded with 1.3, 2.2 and 2.6 mg cm⁻², and Table I shows the corresponding kinetic parameters. In addition Fig. 4 presents some cyclic voltammograms obtained for these electrodes. From Table I it is observed that two regions of Tafel slopes are observed for the smaller Nafion® loadings, which is the typical behavior of the ORR on the Pt catalyst. On the other conditions the second linear region was not observed because it appears together with the diffusion limitations.

For Nation® loadings below 1.75 mg cm⁻² a decrease in E° and an increase in R are observed indicating a diminution of the active area and possibly an increase in electrolyte
resistance. Both phenomena are related to too small an amount of Nafion® impregnated into the electrode, which is insufficient to provide adequate electrolytic conductance inside the catalyst layer, leading to a low platinum utilization and high ohmic drop. In fact, with lower Nafion® loadings there is also the possibility for the gases to reach directly the membrane and then to cause a cross-over phenomenon, which may contribute to the decrease of $E^\circ$. For the highest Nafion® loading (2.6 mg cm$^{-2}$), the increase in $R$, compared with the value for the optimum condition, is possibly related to too large an amount of Nafion® blocking the gas penetration and leading to the appearance of linear diffusion components. In Fig. 3 it is seen that for the smaller Nafion® loadings and for high current densities (or for potentials well below 0.8 V) limiting currents are present. This is clearly related to the smaller active area under such conditions, as observed from the hydrogen adsorption/desorption charges in the cyclic voltammograms of Fig. 4.

Table I shows the effect the catalyst loading on the kinetic parameters for the electrode with 20 wt.% Pt/C containing proportional amounts of Nafion® in the catalyst layer. In the range 0.1 to 0.4 mgPt cm$^{-2}$, the effect of the catalyst loading on the anode was negligible. Regarding the oxygen electrode, several expected phenomena were observed as a function of the platinum loading: (i) the values of $E^\circ$ show that the major effect of the decrease of the catalyst loading is a consistent diminution of the electrochemical active area, although for loadings above 0.2 mgPt cm$^{-2}$ the effect is not crucial for the fuel cell performance and (ii) the linear polarization terms are the same for loadings down to 0.2 mgPt cm$^{-2}$ but increase for 0.1 mg Pt cm$^{-2}$. This indicates the appearance of linear diffusion components, which is related to the decrease in the electrochemical active area.

Figs. 5 and 6 show the ORR polarization results and the cyclic voltammograms obtained for the electrodes with the Pt-V, Pt-Co and Pt-Cr (50-50 atom%) electrocatalysts loaded at 0.4 mg cm$^{-2}$ in the catalyst layer. Compared with pure platinum with the same load, all the alloy catalysts showed inferior performance for the single cell operation (Fig. 5). Because the values of $b$ and $R$ are essentially the same (Table I), these effects of the Pt-alloy catalysts can be only attributed to a diminution of the electrochemical active area, which is confirmed by the values of $E^\circ$ and the cyclic voltammograms of Fig. 6. However, it is important to note that the performances of the alloy electrodes are very much equivalent to those obtained for the electrodes with 0.2 mg cm$^{-2}$ of pure platinum, especially for Cr and V, indicating that the electrochemical activity is completely indifferent to the presence of such metals. For Pt/Co, although the active area is smaller, the polarization curve is similar to that of pure Pt at low current densities which is an indication of a reasonable electrocatalytic activity. This has been also observed for phosphoric acid fuel cells (9).

Fig. 7 and Table I show the effect of the thickness of the membrane for the electrode with 15 % PTFE in the diffusion layer and 20 wt.% Pt/C, 0.1/0.3 (anode/cathode) mgPt cm$^{-2}$ in the catalyst layer. Since the electrodes are the same in all cases, the dispersion in the values of $E^\circ$, especially the high value obtained for the membrane with 125 μm cannot
be attributed to a change in the active area, but must rather be related to an effect of impurities or to other experimental factors not considered in the formulation of equation (1). As expected, a decrease in the values of R with decreasing membrane thickness is observed. It should be recalled that the contributions for the linear polarization terms are related to a contribution of the resistance of the membrane added to the values arising from the polarization resistance of the hydrogen oxidation reaction and the linear diffusion resistance. Taking the resistivity of the membrane as 6.0 Ω cm at 80 °C (6) it is calculated that the contributions of the membrane resistance to the R values should be 0.03, 0.08, and 0.11 Ω cm² for the thicknesses of 50, 125 and 175 μm, respectively. Comparing the above values with those presented in Table I, it is observed that the sum of the linear diffusion component with the HOR polarization is ca. 0.1 Ω cm² for the two thinner membranes. The same calculation made for the 175 μm membrane gave inconsistent results, denoting that the membrane resistance, obtained under conditions of fuel cell operation, is not linear with the thickness. This probably arises as a consequence of a non-uniform water distribution due to proton dragging and back diffusion (6), which is more severe for the thicker membrane.

Figure 8 and Table I present the effect of temperature on the fuel cell behavior and on the kinetic parameters obtained with the electrode with 15% of PTFE in the diffusion layer, and 20 wt.% Pt/C, 0.1 mgPt cm², in the catalyst layer. The only significant effect is a decrease of the values of R with increasing temperature due to the decrease of the membrane resistance. Also, Fig. 8 shows an increase in limiting current with increasing temperature indicating that diffusion problems are less important. This is associated to a decrease of the flooding of the catalyst layer by liquid water, especially in the oxygen electrode (3).

The effect of the partial pressure of oxygen at 80 °C is presented in Figure 8 and Table I for the electrode with 20 wt.% Pt/C, 0.1 mgPt cm² in the catalyst layer and with a diffusion layer with 15% PTFE and 50 μm thickness. The increase in E° observed in Table I for increasing gas pressure is a consequence of the increase of the reversible potential of the fuel cell reactions (as predicted by the Nernst equation) combined with an increase of the exchange current density of the oxygen reduction reaction (iₒ) due to the increase of the gas solubility. Finally, the values of R indicate the presence of linear diffusion component only at the smaller partial pressures. Fig. 8 shows that the observed limiting current densities are not directly proportional to the oxygen pressure. It thus appears that the experimental polarization responses are in contradiction to Henry's law, which may be associated to the appearance of a flooding problem by liquid water, introduced in the gas channels in the catalyst or diffusion layers, which is more crucial when the gas is supplied at higher pressures.
CONCLUSION

The best performance with the locally developed electrodes was obtained with 30 wt.% Pt/C, 0.4 mgPt cm⁻² and 0.7 mg Nafton⁻¹ cm⁻² in the catalyst layer and 15% PTFE and 50 μm thickness in the diffusion layer, for both the cathode and the anode (Fig. 3). However, it was also observed that the platinum requirement can be diminished to values close to 0.2 mgPt cm⁻² in the cathode and 0.1 mgPt cm⁻² in the anode, without significant loss of the characteristics.

Regarding the theoretical interpretation of the cell characteristics two main observations can be made: (i) the Tafel slopes for the ORR are all close to 70 mV dec⁻¹, for potentials above 0.8 V. In some cases a second Tafel slope of ca. 120 mV dec⁻¹ is found for potentials below 0.8 V. Within this picture the Pt/C catalysts show a behavior with respect to the ORR equivalent to a smooth Pt surface; (ii) most of the electroodic systems present limiting currents and some of them also show linear diffusion components arising from diffusion limitations in the gas channels and/or in the thin film of electrolyte covering the catalyst particles. These are the only structural parameters of the electrode which affect the polarization behavior.

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Table I - Kinetic parameters obtained from the fitting of equation (1) to the experimental polarization results for the different electrodes and experimental conditions. The values of \( b \) between parenthesis were obtained at potentials below 0.8 V. Except when mentioned, the conditions were: 0.4 mgPt cm\(^2\), H\(_2\)/O\(_2\) 1/1 atm, \( T = 80 \) °C, Nafion\(^\circledast\) 117 membrane.

| ELECTRODE | \( E^\circ / V \) | \( b / \text{V dec}^{-1} \) | \( R / \Omega \text{ cm}^2 \) |
|-----------|-----------------|-----------------|-----------------|
| Thickness of diffusion layer (μm)\(^{(a)}\) | | | |
| 15        | 0.959           | 0.083           | 0.34            |
| 25        | 0.959           | 0.082           | 0.30            |
| 35        | 0.958           | 0.076           | 0.27            |
| 50        | 0.957           | 0.076           | 0.30            |
| 65        | 0.962           | 0.078           | 0.35            |
| % PTFE in the diffusion layer\(^{(b)}\) | | | |
| 10        | 0.962           | 0.072           | 0.26            |
| 20        | 0.976           | 0.073           | 0.28            |
| 30        | 0.964           | 0.076           | 0.29            |
| 40        | 0.966           | 0.076           | 0.29            |
| 50        | 0.967           | 0.076           | 0.29            |
| Pt/C weight ratio (%)\(^{(c)}\) | | | |
| 10        | 0.958           | 0.076           | 0.30            |
| 20        | 0.965           | 0.075           | 0.28            |
| 30        | 0.963           | 0.071           | 0.30            |
| 40        | 0.960           | 0.078           | 0.30            |
| 60        | 0.915           | 0.072           | 0.39            |
| 80        | -               | (0.116)         | 0.66            |
| Nafion\(^\circledast\) loading (mg cm\(^{-2}\))\(^{(d)}\) | | | |
| 0.87      | 0.861           | 0.078 (0.126)   | 0.89            |
| 1.33      | 0.900           | 0.078 (0.121)   | 0.38            |
| 1.75      | 0.953           | 0.075           | 0.34            |
| 2.20      | 0.958           | 0.076           | 0.30            |
| 2.60      | 0.957           | 0.068           | 0.38            |
| Pt loading (mgPt cm\(^{-2}\)): anode/cathode\(^{(e)}\) | | | |
| 0.1/0.1   | 0.914           | 0.068           | 0.35            |
| 0.1/0.2   | 0.949           | 0.071           | 0.27            |
| 0.1/0.3   | 0.960           | 0.067           | 0.27            |
| 0.1/0.4   | 0.968           | 0.067           | 0.28            |
| 0.4/0.4   | 0.970           | 0.065           | 0.29            |
| Alloy catalyst\(^{(f)}\) | | | |
| Pt-Co     | 0.973           | 0.072           | 0.33            |
| Pt-Cr     | 0.947           | 0.073           | 0.32            |
| Pt-V      | 0.933           | 0.073           | 0.33            |
Table I - cont....

| Membrane thickness (μm) (g) | 50   | 125  | 175  |
|-----------------------------|------|------|------|
|                             | 0.945| 0.964| 0.957|
| Temperature of operation (°C) (h) | 50   | 50   | 50   |
|                             | 0.913| 0.913| 0.913|
| Hydrogen/Oxygen (partial) pressure (h) | 1/0.2| 2/0.6| 1/1  |
|                             | 0.900| 0.914| 0.914|

(a) electrodes with 10 wt.% Pt/C, 2.2 mg cm⁻² of Nafion® in the catalyst layer and 40 % PTFE in the diffusion layer.
(b) electrodes with 20 wt.% Pt/C, 1.1 mg cm⁻² of Nafion® in the catalyst layer and 35 μm for the thickness of the diffusion layer.
(c) electrodes with 2.2, 1.1, 0.73, 0.55, 0.37, and 0.28 mg cm⁻² of Nafion® in the catalyst layer, respectively. Diffusion layers with 40% PTFE and 35 μm thickness.
(d) electrodes with 10 wt. % Pt/C, 40 % PTFE in the diffusion layer with a thickness of 35 μm.
(e) electrodes with 20 wt.% Pt/C and proportional amounts of Nafion® in the catalyst layer taking as reference 1.1 mg Nafion® cm⁻² for the 0.4 mgPt cm⁻² electrode. Diffusion layer with 15% PTFE and 50 μm thickness.
(f) electrodes with 0.4 mgPt-alloy cm⁻². Electrodes with 20 wt.% Pt-alloy/C in the catalyst layer. Diffusion layer with 15% PTFE and 50 μm thickness.
(g) electrodes with 20 wt.% Pt/C, 0.1/0.3 mgPt cm⁻² (anode/cathode). Diffusion Layer with 15 % PTFE and 50 μm.
(h) electrodes with 20 wt.% Pt/C 0.1 mgPt cm⁻² (cathode and anode). Diffusion Layer with 15 % PTFE and 50 μm.
1.0

Fig. 1 - Cell potential-current density plots for H₂/O₂ 1 atm PEFC single cells at 80 °C for the 10 wt.% Pt/C, 0.4 mgPt cm⁻², 2.2 mg Nafion® cm⁻² electrodes with several thicknesses of the diffusion layer (40 % PTFE): (+) 15; (o) 35; (A) 65 μm. Hydrogen humidifier at 95 °C; oxygen humidifier at 85 °C. Nafion® 117 membrane.

1.0

Fig. 2 - Cell potential-current density plots for H₂/O₂ 1 atm PEFC single cells at 80 °C for the 20 wt.% Pt/C, 0.4 mgPt cm⁻², and 1.1 mg Nafion® cm⁻² electrodes with several PTFE contents in the diffusion layer: (+) 10, (O) 30 and (Δ) 50 % PTFE. Diffusion layer with 35μm thickness. Hydrogen humidifier at 95 °C; oxygen humidifier at 85 °C. Nafion® 117 membrane.
Fig. 3 - Cell potential-current density plots for H₂/O₂ 1 atm PEFC single cells at 80 °C for the electrodes prepared with several Pt/C (wt.%) - Nafion loading (mg cm⁻²):
Diffusion layer with 40% PTFE and 35 μm thickness: (□) 10 - 1.3; (V) 10 - 2.2; (O) 10 - 2.6; (Δ) 60 - 0.4. Diffusion layer with 15% PTFE and 50 μm thickness: (+) 20 - 1.1; (◊) 30 - 0.7. Hydrogen/oxygen humidifiers at 95/85 °C; Nafion® 117 membrane.

Fig. 4 - Cyclic voltammetry obtained at 25 °C for the electrodes with 10 wt.% Pt/C, 0.4 mgPt cm⁻², and several Nafion® loadings in the catalyst layers: (a) 1.3; (b) 2.2; and (c) 2.6 mg cm⁻². v = 50 mV s⁻¹. Diffusion layer with 15% PTFE and 50 μm thickness. Nafion® 117 membrane.
Fig. 5 - Cell potential-current density plots for H₂/O₂ 1 atm PEFC single cells at 80 °C for the 20 wt.% Pt-alloy/C for the several alloy catalysts with optimized Nafion loadings: (□) Pt; (V) Pt-V; (Δ) Pt-Co, (O) Pt-Cr. Diffusion layer with 50 μm and 15% PTFE. Hydrogen humidifier at 95 °C; oxygen humidifier at 85 °C. Nafion® 117 membrane.

Fig. 6 - Cyclic voltammetries obtained at 25 °C for the electrodes with the different alloys loaded to the catalyst layers: (a) Pt/C; (b) Pt-Co/C; (c) Pt-V/C and (d) Pt-Cr/C. v = 50 mV s⁻¹. Nafion® 117 membrane.
Fig. 7 - Cell potential-current density plots for H₂/O₂ 1 atm PEFC single cells at 80 °C for the 20 wt.% Pt/C, hot-pressed to Nafion® membranes with several thicknesses: (□) Nafion® 112 (50 µm), (o) Nafion® 115 (124 µm) and (Δ) Nafion® 117 (175 µm). Electrodes with 0.1/0.3 mgPt cm⁻² (anode/cathode) and proportional amounts of Nafion® taking as reference 1.1 mg cm⁻² for 0.4 mgPt cm⁻². Diffusion layer with 15 % PTFE and 50 µm thickness. Hydrogen humidifier at 95 °C, oxygen humidifier at 85 °C. Nafion 117 membrane.

Fig. 8 - Cell potential-current density plots for PEFC single cells at 80 °C for the 20 wt.% Pt/C, 0.1 mg Pt cm⁻² at several cell temperatures and gas pressures (H₂/O₂): (□) 50 °C, 1/1 atm; (o) 80 °C, 1/1 atm; (Δ) 80 °C, 2/5 atm and (V) 80 °C, 1/0.2 atm. Diffusion layer with 15 % PTFE and 50 µm thickness. Nafion 117 membrane.