

Polymer electrolyte fuel cells based on bimetallic carbon nitride electrocatalysts[☆]

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Abstract

In this work, two new bimetallic carbon nitride electrocatalysts, based on platinum and either nickel or iron, are tested in a single-cell PEMFC. The membrane electrode assembly (MEA) is prepared using the proposed electrocatalysts at the cathodic side and two different reference materials at the anode. MEA performance is extensively tested in both kinetically controlled ($V > 0.9$ V) and “operative” ($V \approx 0.65$ V) regimes, with both air and pure oxygen as oxidants. Electrochemical information on the performance of cathodic electrodes is also obtained by carrying out measurements with the “driven cell” method. The proposed materials show very high activity in both operating regimes and, with respect to the reference electrocatalysts, exhibit a lower overpotential (~ 40 mV) towards the ORR.

Interestingly, only a lower mass of platinum is necessary to obtain the same electrical power (up to $0.61 \text{ g}_{\text{Pt}} \text{ kW}^{-1}$ vs. $1.1 \text{ g}_{\text{Pt}} \text{ kW}^{-1}$ of the reference MEA), leading to the possibility of producing cheaper MEAs. The electrochemical surface area of the proposed materials is larger than that of reference electrocatalysts. Lastly, the active sites of these bimetallic carbon nitride electrocatalysts are much less susceptible to CO poisoning.
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Keywords: PEM fuel cells; Bimetallic carbon nitride electrocatalysts; MEA preparation; Cathode electrodes; Platinum mass efficiency; CO tolerance

1. Introduction

Polymer electrolyte membrane fuel cells (PEMFCs) are a class of devices used for the conversion of chemical energy into electrical energy. Recently, they have aroused great interest in both academic and industrial research due to their efficiency (as high as 65%) [1], which is much better than that characterizing internal-combustion engines (no higher than ca. 40%, due to Carnot limits). Furthermore, PEMFCs fed with hydrogen do not produce greenhouse gases such as CO_2 , making them viable candidates for the implementation of a delocalized, environment-friendly, power generation infrastructure [2]. Lastly, PEMFCs are light and compact systems, characterized by very high power densities and capable of operating at relatively

low temperatures (under 120°C) [3]. These characteristics make them particularly interesting for applications in the automotive industry and in portable electronics [4,5].

Nevertheless, there are still important drawbacks, involving costs and durability issues, to be solved before widespread use of PEMFCs can begin. In particular, one significant bottleneck in PEMFC operation lies in the cathode electrode, where the oxygen reduction reaction (ORR) takes place [6]. The current state of the art of cathode electrodes consists of the use of nanometric platinum crystals supported on carbons with a large surface area [6]. The ORR is very slow and results in a very large overpotential, which leads to significant degradation of cell performance [7]. Recent studies show that alloying platinum with other first-row transition metals such as Fe [8], Ni and Co gives rise to enhanced performance of PEMFCs, in terms of both operating potential and current density [6,9]. Recent experiments performed by our group show that supporting bimetallic clusters, composed of Pt and another first-row transition metal (e.g., Pt–Fe [10], Pt–Ni [11,12], and Pd–Co combinations [13]) on carbon nitride materials, yield electrocatalysts with intrinsic enhanced perfor-

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mance toward the ORR, as determined by CV-TF-RDE studies [14]. In this work, the bimetallic carbon nitride electrocatalysts, prepared according to the rationale previously described in the literature [15], were used to assemble MEAs for the first time and studied in a single PEMFC in real operative conditions.

2. Experimental

2.1. Preparation of electrocatalysts

The procedure used to prepare the ORR electrocatalysts described in this work is reported in the scientific and technical literature [10–13,15]. Briefly, two solutions containing anionic complexes of the desired metals, such as PtCl_4^{2-} and $\text{Ni}(\text{CN})_4^{2-}$ for Pt–Ni–CN 580 and PtCl_6^{2-} and $\text{Fe}(\text{CN})_6^{3-}$ for Pt–Fe–CN 900, were mixed in the presence of sucrose as organic binder. The result was a very fine suspension for the Pt–Ni–CN 580 or a compact gel for the Pt–Fe–CN 900. These precursors were dried in a rotovapor and underwent thermal treatment in a dynamic vacuum of 10^{-3} mbar. The precursor of the Pt–Ni–CN 580 material was dried at 180°C for 24 h, decomposed at 300°C for 2 h, and thermally treated at 580°C for 2 h. The precursor of the Pt–Fe–CN 900 material was dried at 200°C for 12 h, and thermally treated at 900°C and at 700°C for 1 and 4 h, respectively. The resulting products were finely ground, washed three times with Milli-Q water, treated with H_2O_2 10% vol., and finally dried under an IR lamp in order to yield the final materials. Chemical analysis was performed as described in the literature by ICP-AES and microanalysis [11]. The compositional results of the products are listed in Table 1. EC-20 and EC-20/10 electrocatalysts (Electrochem Inc.) were used as references. The electrocatalysts were indicated with the label Pt–M–CN X, where M singles out the metal Ni or Fe and X the temperature of the final thermal treatment of the precursors.

2.2. Preparation of MEAs

11.99 mg of Pt–Ni–CN 580 was ball-milled for 1 h together with 11.90 mg of XC-72R carbon black, yielding a homogeneous mixture. The resulting black powders were quantitatively transferred into a small glass vial, to which 200 μL of Milli-Q water and 2 mL of isopropyl alcohol were added. This suspen-

sion was sonicated for 2 h before 191 μL of a commercial Nafion 5% solution (Aldrich) was added. The ink was homogenized by sonication for 2 h, and deposited onto a blank made of a sheet of reinforced Teflon with an area of 4 cm^2 ($2\text{ cm} \times 2\text{ cm}$). The solvents were removed under an IR lamp. Similar electrodes were prepared using Pt–Fe–CN 900, EC-20 and EC-20/10. XC-72R was added in a 1:1 weight ratio to the Pt–Fe–CN 900 material. All the electrodes were characterized by a platinum loading of about 0.5 mg cm^{-2} . The amount of Nafion solution added to the inks was determined with the aim of obtaining a carbon/Nafion weight ratio of 0.3 [16]. The desired combinations of anode and cathode electrodes were transferred to a Nafion 117 (N117) membrane (Ion Power) by hot pressing at 120°C for 2 min at a pressure of ca. 68 bar. The Teflon blanks were then peeled off and the desired catalyst-coated membrane (CCM) was obtained [17]. Precise determination of the platinum mass effectively transferred to each membrane was achieved by comparing the weight of the blanks before and after the electrode transfer process. The measured platinum loading for each electrode was about 0.4 mg cm^{-2} . Gas diffusion layers (GDL) were prepared using the following protocol. 25 mg of XC-72R carbon black were dispersed in a solution consisting of 500 mg of glycerol (Aldrich), 2 mL of isopropyl alcohol, 500 μL of water, and 5.6 μL of a Teflon dispersion (D1214-X, Solvay). The resulting suspension was homogenized by sonication for 2 h, after which 200 mg was used to impregnate a 4 cm^2 ($2\text{ cm} \times 2\text{ cm}$) piece of a GDL AvCarbTM 1071 HCB carbon fabric (Ballard). These impregnated GDLs underwent the following thermal treatment: 120°C for 10 min, 280°C for 10 min, and 350°C for 10 min [18]. The MEAs were obtained by hot pressing two gas-diffusion layers onto the CCM at 120°C for 2 min at a pressure of ca. 68 bar. The MEAs were then washed in H_2SO_4 1 M, soaked in H_2O_2 3% vol., and finally rinsed three times in Milli-Q water. Each step lasted 1 h and was performed at 80°C . In this study, both Pt–Ni–CN 580 and Pt–Fe–CN 900 were used as cathode catalysts, mounting either EC-20 or EC-20/10 at the anode. A total of four MEAs were assembled as follows: EC-20/N117/Pt–Ni–CN 580, EC-20/10/N117/Pt–Ni–CN 580, EC-20/N117/Pt–Fe–CN 900, EC-20/10/N117/Pt–Fe–CN 900. A commercial MEA (ElectroChem Inc.) with an active area of 1 cm^2 and mounting the EC-20 catalyst with a loading of 1 mg Pt cm^{-2} on both anodic and cathodic sides, was used as reference and tested in exactly the same conditions.

Table 1
Chemical composition of catalyst materials

Material	Weight %						Formula
	Pt ^a	M ^a	K ^a	C ^b	N ^b	H ^b	
Pt–Ni–CN 580	15.22	Ni = 9.17	4.0	42.96	2.3	1.02	$\text{K}_{1.29}[\text{PtNi}_{1.97}\text{C}_{45}\text{H}_{13}\text{N}_{2.1}]$
Pt–Fe–CN 900	17.93	Fe = 8.17	0.78	60.32	0.16	–	$\text{K}_{0.12}[\text{PtFe}_{1.6}\text{C}_{55}\text{N}_{0.12}]$
EC-20 ^c	20	–	–	80	–	–	[PtC ₆₅]
EC-20/10 ^c	20	Ru = 10	–	70	–	–	[PtRu _{0.97} C ₅₇]

^a Determined by ICP-AES spectroscopy.

^b Determined by elemental analysis.

^c Commercial material produced by Electrochem Inc. Nominal values.

2.3. Single cell tests

The electrochemical activity of the cathodic electrocatalysts was evaluated using pure hydrogen as a fuel and both air and pure oxygen as oxidants. The temperatures of the cell and gases were 80 and 87 °C, respectively. The hydrogen and oxidant flow rates were 800 and 2000 sccm, respectively. The back pressure of the fully humidified gases was kept at 4 bar. Single cell tests were carried out in a 5 cm² single cell with one-channel serpentine flowfields for both anodic and cathodic sides. The channels were 1 mm wide and 0.5 mm deep. The plates were made of graphite. MEA performance was determined as follows. Polarization curves were collected continuously from open-circuit potential (OCP) up to 0.1 V at 5 mA s⁻¹, until the system reached stability. The final polarization curve was collected immediately afterward. MEA performance in the kinetically controlled regime was evaluated by collecting a polarization curve at 0.1 mA s⁻¹ from OCP up to ca. 0.85 V. MEA performance with pure oxygen as oxidant was determined according to the same protocol. The polarization curves were not corrected for internal resistance losses.

2.4. “Driven cell” tests

Further electrochemical information on the performance of the cathode electrodes was determined with the “driven cell” technique [19]. Briefly, the cathode and anode of the MEAs are fed with fully humidified inert gas (Ar) and pure hydrogen, respectively. The flow rates are set at 800 and 2000 sccm for anode and cathode, respectively. The cell operates at 25 °C and the backpressure of both gases is set at 340 mbar. An external potentiostat/galvanostat (model 263A, EG&G Instruments) is used to “drive” the cell with the cathode of the MEA acting as the working electrode, and the anode as both reference and counter electrode. Cyclic voltammograms were collected at 10 mV s⁻¹ from 0.05 to 1.3 V. CO stripping measurements were made in the “driven cell” mode according to a previous procedure [20]. Fully humidified carbon monoxide was fed at 500 sccm at the cathode of the MEA for 10 min, and its adsorption was externally driven with the working electrode kept at 0.2 V versus the anode. The physisorbed CO was later removed by feeding the cathode with fully humidified inert gas for 15 min, with the working electrode kept at OCP. CO stripping was performed by sweeping the MEA cathode at 20 mV s⁻¹ from 0.05 to 1.3 V versus NHE. The completeness of CO removal was evaluated by cycling the cathode between 0.05 and 1.3 V at 20 mV s⁻¹ for 10 min. The experimental protocol described here was applied to two MEAs: EC-20/N117/Pt–Ni–CN 580 and EC-20/N117/Pt–Fe–CN 900. The former was tested with both electrodes as the cathode, alternately; the latter was tested once with Pt–Fe–CN 900 material as cathode.

3. Results and discussion

3.1. Single cell tests

The polarization and corresponding power curves of both commercial reference and home-made MEAs, fed with either air

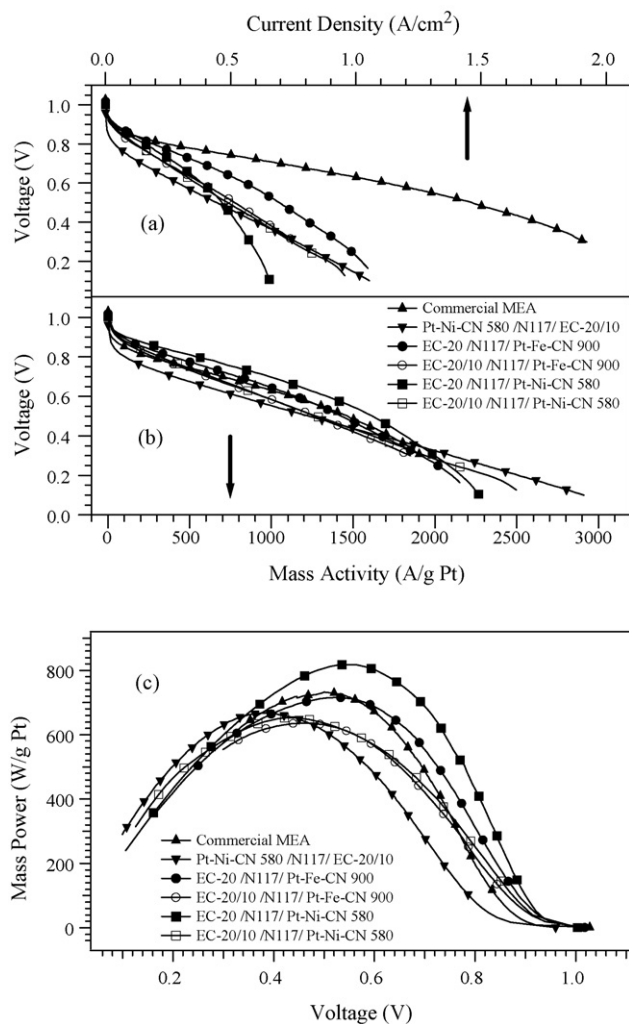


Fig. 1. Polarization curves normalized on the active area (a) and on platinum mass present on the cathodic electrode (b); electrical power (c) of prepared MEAs. Tests were carried out with a 5 cm² single cell operating with pure H₂ on anode and air at cathode. H₂/air flow was 800 and 2000 sccm at 100% RH.

or pure oxygen at the cathode, are shown in Figs. 1 and 2, respectively. The EC-20/10/N117/Pt–Ni–CN 580 MEA was tested with Pt–Ni–CN 580 as both anodic and cathodic electrocatalyst. The proposed Pt–Ni–CN 580 and Pt–Fe–CN 900 materials had higher platinum mass activities with respect to the commercial MEA, especially at $V > 0.65$ V. The polarization curves collected at 0.1 mA s⁻¹ were used to obtain Tafel plots and to evaluate the open-circuit potential of the MEAs, according to the procedure described by Kocha [16]. Results are shown in Fig. 3. The overall performance of the MEAs presented here was evaluated by defining four figures of merit: (a) platinum mass activity at 0.9 V (Fig. 4); (b) platinum mass activity at 0.65 V (Fig. 5); (c) mass efficiency (Fig. 6); (d) open-circuit potential (Fig. 7). Platinum mass activity at 0.9 V was used to evaluate the performance of the cathodic materials in a region where the operation of the cell is essentially limited by the ORR [16]. The open-circuit potential was determined using the Tafel plots of Fig. 3, as the potential where $\log(i_{\text{kin}}) = 0$. Both figures of merit were derived from the polarization curves collected in the high potential region

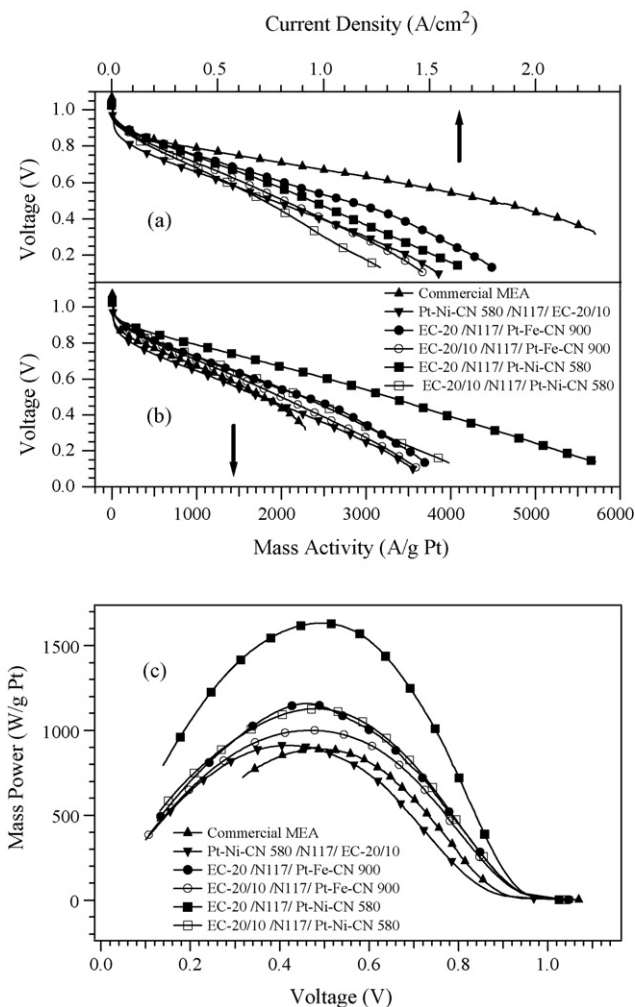


Fig. 2. Polarization curves normalized on the active area (a) and on platinum mass present on the cathodic electrode (b); electrical power (c) of prepared MEAs. Tests were carried out with a 5 cm² single cell operating with pure H₂ on anode and pure O₂ at cathode. H₂/O₂ flow was 800 and 2000 sccm at 100% RH.

(V > 0.85 V) at 0.1 mA s⁻¹. These conditions were adopted with the aim of excluding as much as possible spurious contributions due to internal resistance losses of the MEAs or capacitive currents. Proof of the quality of these assumptions may be found in the slopes of the Tafel plots, which were close to the value of 60 mV per decade for all analyzed cells. This value is typical of a four-electron mechanism for the ORR on a platinum electrocatalyst [16,21]. The other two figures of merit, which are important from a practical point of view, were determined from the overall polarization curves (Figs. 1 and 2) and are platinum mass activity at 0.65 V and mass efficiency. Platinum mass activity at 0.65 V allowed us to evaluate MEA performance in a situation close to that commonly found in real operating conditions [16,22]. Mass efficiency was considered as the minimum mass of platinum necessary to produce 1 kW of electrical power. This parameter corresponds to the reciprocal of the maximum mass power measured on the power curves shown in Figs. 1b and 2b. The proposed Pt–Ni–CN 580 and Pt–Fe–CN 900 materials give rise to a distinctly better performance with respect to that observed

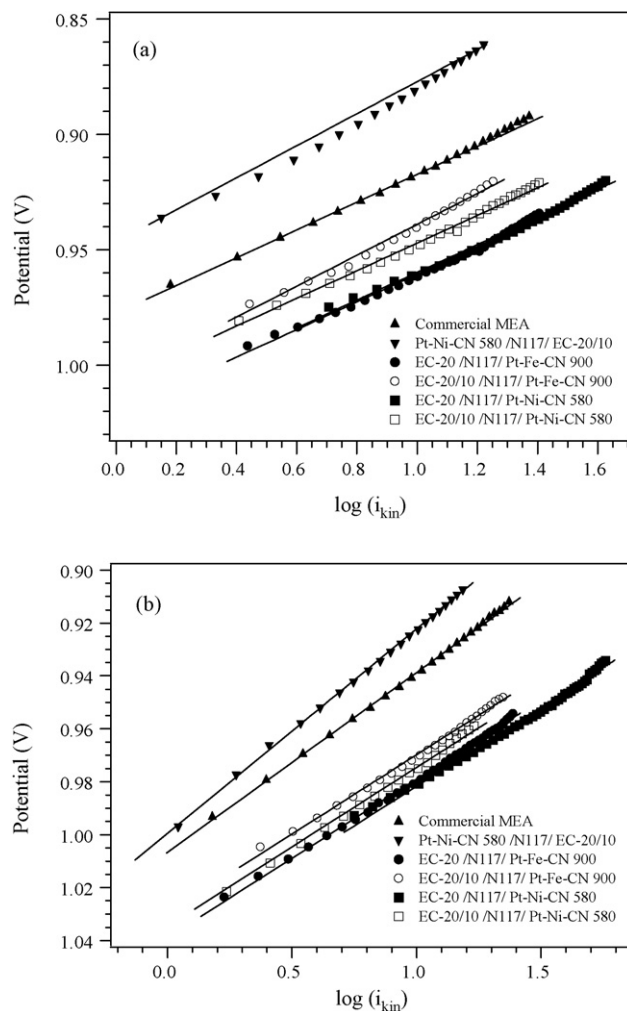


Fig. 3. Tafel plots of polarization curves collected at 0.1 mA s⁻¹. Cathode fed with air (a) and pure oxygen (b). Values were normalized on platinum mass present on each cathodic electrode. Other operating conditions as in Fig. 1.

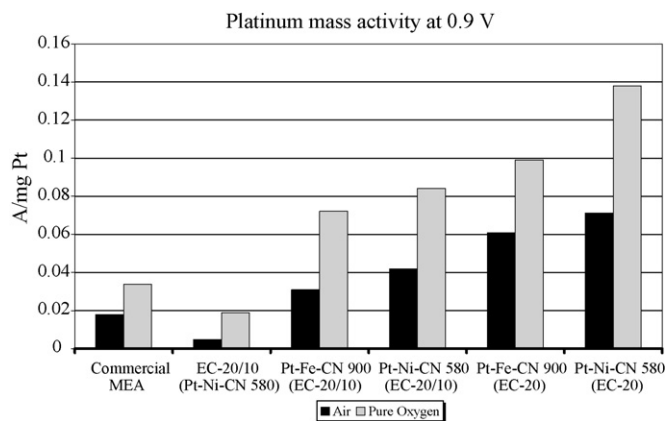


Fig. 4. Platinum mass activity at 0.9 V. Tests performed in a 5 cm² single cell operating with pure H₂ on anode and air or pure oxygen at cathode. Values were normalized on platinum mass present on each cathodic electrode. Other operating conditions as in Fig. 1.

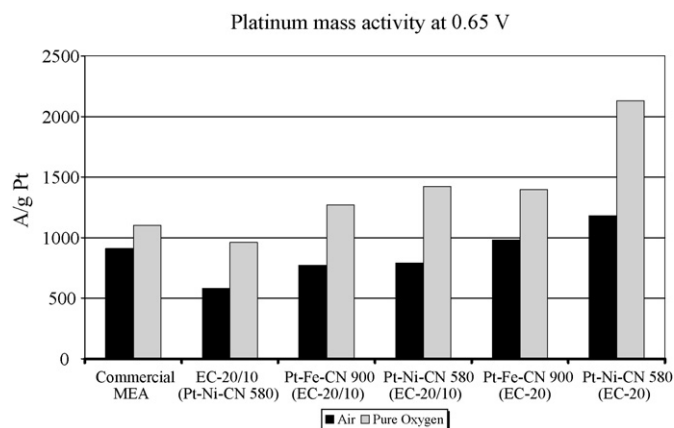


Fig. 5. Platinum mass activity at 0.65 V. Tests performed in a 5 cm² single cell operating with pure H₂ on anode and air or pure oxygen at cathode. Values were normalized on platinum mass present on each cathodic electrode. Other operating conditions as in Fig. 1.

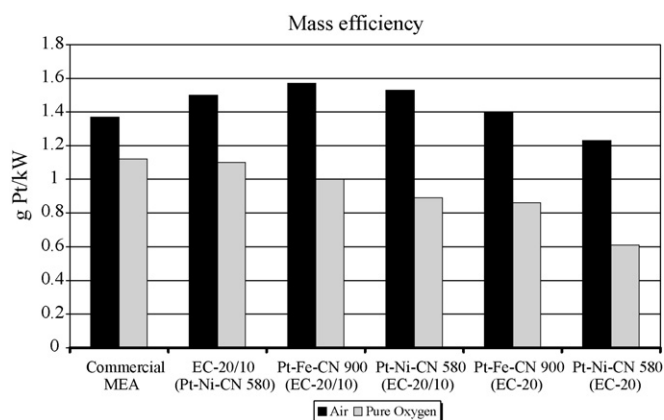


Fig. 6. Mass efficiency of electrocatalysts in cathodic side of prepared MEAs. Tests performed in a 5 cm² single cell operating with pure H₂ on anode and air or pure oxygen at cathode. Values were normalized on platinum mass present on each cathodic electrode. Other operating conditions as in Fig. 1.

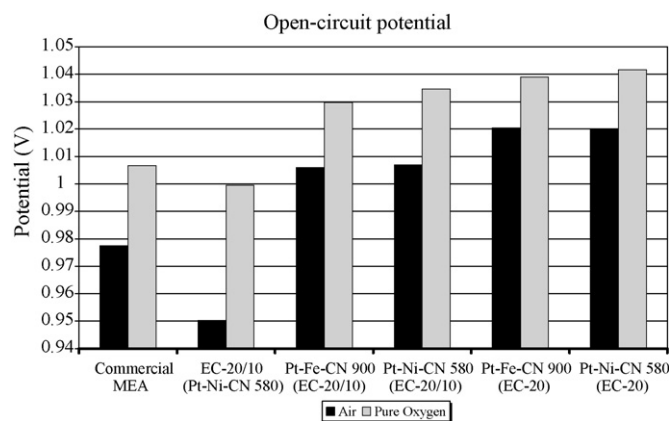


Fig. 7. Open-circuit potential of tested MEA. Tests performed in a 5 cm² single cell operating with pure H₂ on anode and air or pure oxygen at cathode. Values were normalized on platinum mass present on each cathodic electrode. Other operating conditions as in Fig. 1.

for EC-20 and EC-20/10 at $V > 0.85$ V. In accordance with the CV-TF-RDE studies described elsewhere [10–13], this result was attributed to the lower overpotential registered in the ORR of the bimetallic active sites of carbon nitride electrocatalysts. The lowest overpotential value in the ORR was recorded for the Pt–Ni–CN 580 material. The performance of the home-made MEAs mounting the EC-20 catalyst on the anodic side is better than that obtained with the EC-20/10, in both terms of open-circuit potential and mass activity at 0.9 V. This result indicates that, with respect to the electrocatalyst based on pure crystalline platinum nanoparticles (EC-20), the Pt–Ru commercial catalyst (EC-20/10) has a higher overpotential in the hydrogen oxidation reaction (HOR). The overpotential of Pt–Ni–CN 580 in the HOR is essentially similar to that of the EC-20 (data not shown), indicating that the poor performance of the MEA Pt–Ni–CN 580/N117/EC-20/10 is associated with the reduced activity of EC-20/10 as a cathodic electrocatalyst. MEA performance at potentials lower than 0.9 V is affected by several factors, such as the electrical resistance of the various components and interfaces and transport phenomena of reagents and water [16]. In addition, it should be observed that both Pt–Ni–CN 580 and Pt–Fe–CN 900 materials at $V < 0.9$ V perform in MEAs better than commercial references, thus confirming the trend observed in the region under kinetic control. This evidence suggests that, in our MEAs, the activity of the cathode electrocatalysts is the main discriminating parameter in determining the overall performance of the cell. Taken together, these results allow us to conclude that, if MEAs are fed with pure oxygen at the cathode (Fig. 8), an increase in cell performance is observed for both bimetallic carbon nitride electrocatalysts with respect to the commercial reference.

3.2. “Driven cell” tests

Fig. 9 shows the cyclic voltammograms of MEAs prepared using the Pt–M–CN electrocatalysts (M = Ni or Fe). These measurements were performed by filling the cathodic and anodic side-compartments of a single PEMFC with argon and hydrogen gas, respectively, and using the anode as both reference and counter-electrode. With respect to the commercial EC-20 reference (Fig. 9c), the cyclic voltammograms of the MEAs mounting either Pt–Ni–CN 580 (Fig. 9a) or Pt–Fe–CN 900 (Fig. 9b) in the cathodic side feature a much larger contribution, associated with capacitive phenomena. In accordance with other results [10,11], the latter phenomena are associated with the rougher morphology and nanoporosity of the proposed materials. This evidence is interpreted by admitting that, with respect to the commercial reference, the Pt–M–CN materials are endowed with a higher surface area. These results are in accordance with the CV-TF-RDE, morphology and XRD studies carried out elsewhere on Pt–M–CN electrocatalysts [10,11]. Indeed, it was determined that the active platinum surface area of the EC-20 material, evaluated using adsorption–dissociation peaks as described in the literature, was about 67 m² g_{Pt}^{−1} [6,23], quite in line with previously reported values. This method could not be applied to the voltammograms of the Pt–M–CN materials shown in Figs. 9b and c, owing to the capacitive contribution which masks

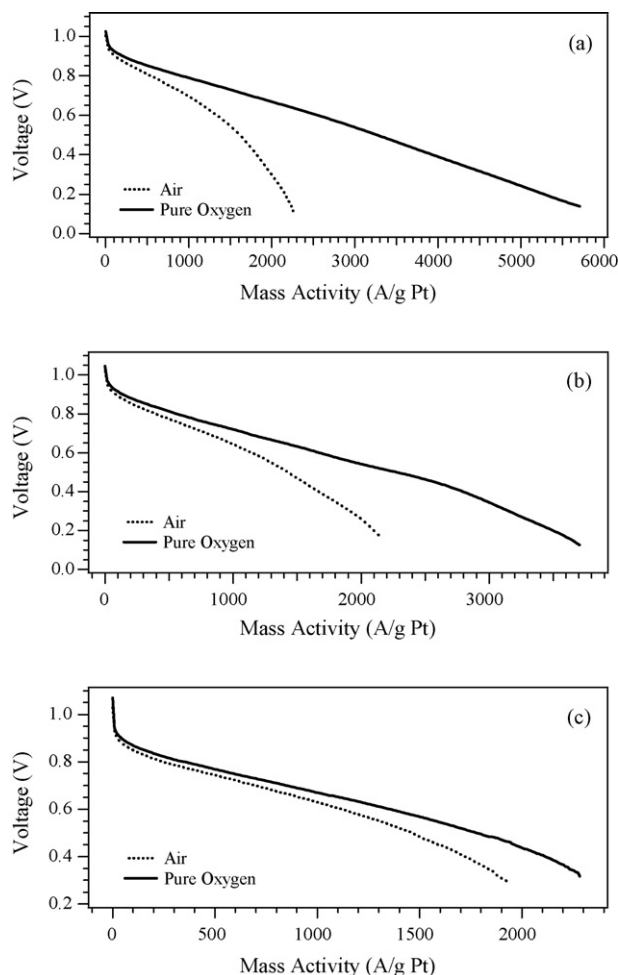


Fig. 8. Comparison of polarization curves of some selected MEAs. Measurements carried out in a 5 cm^2 single cell operating with pure H_2 on anode and air or pure oxygen at cathode. (a) EC-20/N117/Pt-Ni-CN 580; (b) EC-20/N117/Pt-Fe-CN 900; (c) commercial MEA mounting EC-20 at both the anode and the cathode. Values were normalized on platinum mass present on each cathodic electrode. Other operating conditions as in Fig. 1.

the features ascribable to the hydrogen adsorption–dissociation processes of the materials. These results are in accordance with the CV-TF-RDE measurements [10–13] and indicate that the structure of Pt–M–CN materials is different from that of electrocatalysts consisting of polycrystalline platinum particles supported on graphitic materials.

Voltammetric stripping of CO adsorbed irreversibly on platinum is an important tool in order to gain information on the surface structure of materials [24,25] and to determine the electrochemical surface area of supported platinum electrocatalysts [20,23]. Results of CO stripping measurements performed on the single cell mounting the EC-20 catalyst (Fig. 10c) are consistent with those described in the literature [23]. Furthermore, as shown in Figs. 10a and b, Pt–M–CN materials are much less prone to adsorbing CO irreversibly. This evidence was attributed to the structure of the bimetallic active sites of Pt–M–CN electrocatalysts, which consists of bimetallic clusters, composed of a Pt(0) atom coordinated in square planar coordination geometry by two nitrogen atoms of the pyridine rings of the carbon nitride

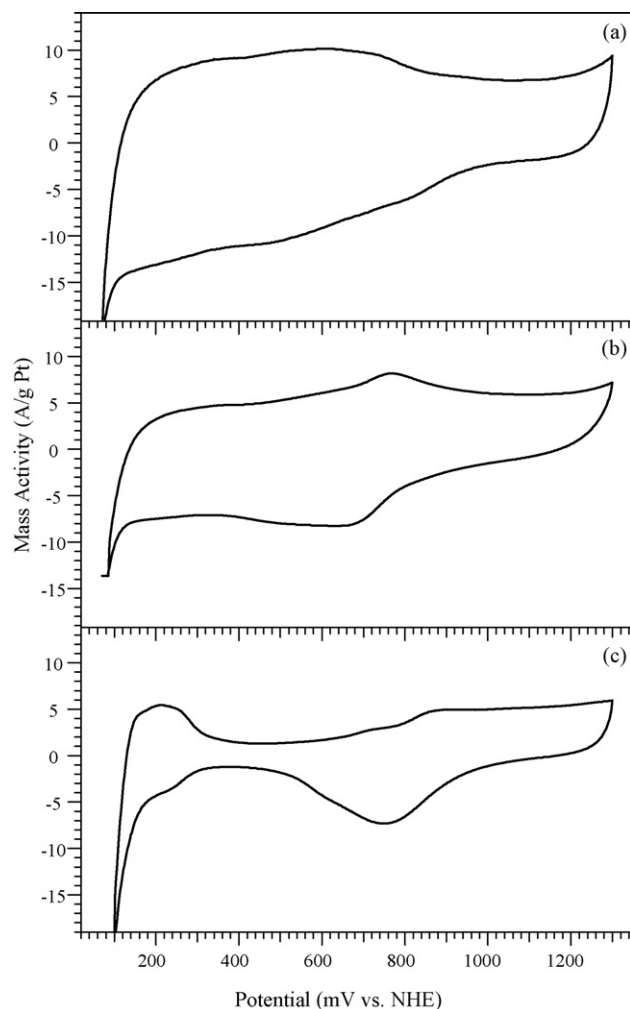


Fig. 9. Cyclic voltammograms measured in “driven cell” mode. Measurements carried out with a 5 cm^2 single PEMFC with configurations EC-20/N117/Pt-Ni-CN 580 (a); EC-20/N117/Pt-Fe-CN 900 (b); Pt-Ni-CN 580/N117/EC-20 (c). Cell was operated with pure H_2 on the anode and pure argon on cathode. Values were normalized on platinum mass present on cathodic electrode. H_2/Ar flows were respectively 800 and 2000 sccm with 100% RH.

graphitic layer and by two bridging cyanide groups. These bridge the square planar coordinated platinum complexes with two octahedrally coordinated transition metal atoms such as Fe and Ni, which are present in their neighborhood in an oxidized state. Fe(III) and Ni(II) complete their octahedral coordination geometry with hydroxyl ligands [11,10]. The proposed structural model for the active sites on the carbon nitride support explains the excellent catalytic performance of the electrocatalysts studied here. Indeed, the presence of highly acid hydroxyls coordinated on Fe(III) and Ni(II) complexes near Pt active sites efficiently catalyzes the elimination of ORR products. The result is a very active electrocatalyst for both ORR and HOR processes. In addition, the fact that no peak is observed at 850 mV (Fig. 10a and b) after CO treatment is a very exciting result, which confirms that the clusters of Pt and M bimetallic complexes supported on the surfaces of the carbon nitride bulk particles protect the platinum from CO poisoning. These results indicate bimetallic carbon nitride electrocatalysts as promising materials for appli-

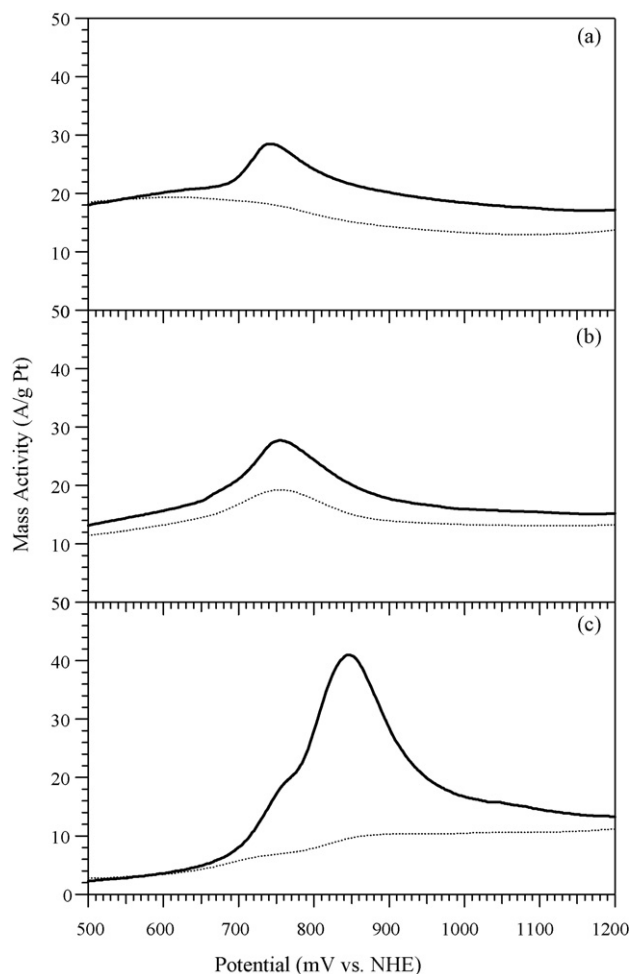


Fig. 10. CO stripping sweeps of the MEAs measured in “driven cell” mode. First stripping sweep (solid lines). Sweeps after CV cycling (dotted lines). Tests performed on a 5 cm^2 single cell with configurations EC-20/N117/Pt–Ni–CN 580 (a); EC-20/N117/Pt–Fe–CN 900 (b); Pt–Ni–CN 580/N117/EC-20 (c). Values were normalized on platinum mass present on cathodic electrode. The cell was operated with pure H_2 at the anode and pure argon or CO at the cathode. The $\text{H}_2/\text{Ar}/\text{CO}$ flows were respectively 800, 2000 and 500 sccm at 100% RH.

cations in DMFCs and PEMFCs, thanks to their platinum mass activity and lack of severe poisoning by CO.

4. Conclusion

The proposed Pt–Ni–CN 580 and Pt–Fe–CN 900 materials proved to be promising electrocatalysts for mounting on the cathode of PEMFCs. Preliminary results of tests performed with the CV-TF-RDE method [10–12] were thus confirmed. In particular, in comparison with the reference materials, the proposed bimetallic carbon nitride electrocatalysts have a lower overpotential toward the ORR ($\sim 40\text{ mV}$), which is responsible for the higher open-circuit potential and mass activity of these materials at 0.9 V (e.g., $0.099\text{ A mg}_{\text{Pt}}^{-1}$ for the Pt–Fe–CN 900 material versus $0.034\text{ A mg}_{\text{Pt}}^{-1}$ for the EC-20 reference in a pure oxygen atmosphere). The performance of Pt–M–CN materials proved better than that of reference systems, even at lower potentials and in conditions more similar to those found during

real cell operation, especially when the MEAs were fed with pure oxygen (e.g., $1395\text{ A g}_{\text{Pt}}^{-1}$ for the Pt–Fe–CN 900 material vs. $1100\text{ A g}_{\text{Pt}}^{-1}$ for the EC-20 reference in a pure oxygen atmosphere) at 0.65 V . In addition, the amount of platinum needed to produce 1 kW of electrical power was lower (e.g., $0.86\text{ g}_{\text{Pt}}\text{ kW}^{-1}$ for the Pt–Fe–CN 900 material vs. $1.12\text{ g}_{\text{Pt}}\text{ kW}^{-1}$ for the EC-20 reference in a pure oxygen atmosphere), making the production of cheaper MEAs feasible. Further information on the electrochemical performance of Pt–M–CN materials was obtained by carrying out “driven cell” measurements. A large surface area was detected and the peculiar nature of the structure of the active sites was highlighted, which proved to be very different from that found in typical commercial reference catalysts. A very low affinity toward irreversible CO adsorption was evidenced, making Pt–M–CN materials very promising for all applications in which this phenomenon is a hindrance, such as the cathode of DMFCs and the anode of PEMFCs fed with hydrogen obtained from reformed hydrocarbons.

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