

Effect of Two Anodic Materials and $\text{Ru}_x\text{Mo}_y\text{Se}_z$ as a Cathode Catalyst on the Performance of Two Single Chamber Microbial Fuel Cells

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Abstract: The objectives of this work were to evaluate (i) the application of a bimetallic chalcogenide, $\text{Ru}_x\text{Mo}_y\text{Se}_z$, as an oxygen reduction reaction (ORR) catalyst and (ii) the effect of the type of two anodic materials on the performance of two microbial fuel cells (MFCs). A single chamber MFC-T was built with a plexiglass cylinder, the two extreme circular faces were fitted with PEM-cathode assemblage, i.e., left and right faces. The anode consisted of 65 small triangular pieces of graphite filling the anodic chamber. A second MFC-C had a 'sandwich' arrangement anode-PEM-cathode. The cathodes were made of flexible carbon-cloth containing catalysts loading of $1\text{mg}/\text{cm}^2$ $\text{Ru}_x\text{Mo}_y\text{Se}_z$ or $0.5\text{mg}/\text{cm}^2$ Pt. Power derived by cell T with cathode chalcogenide catalyst was 43% inferior to that of a similar cell with Pt although the cost of the first catalyst is significantly lower than that of Pt, i.e., 73% lower. Finally, application of graphite anode made of small triangular pieces significantly improved the performance of a MFC-T that used $\text{Ru}_x\text{Mo}_y\text{Se}_z$ as a cathodic catalyst for ORR.

Keywords: anodic material; carbon cloth; chalcogenide; graphite; internal resistance; microbial fuel cell; series;parallel

1. INTRODUCTION

Microbial fuel cells (MFC) constitute a promising technology for sustainable production of alternative energy and waste treatment [1]. Platinum has been commonly used as a catalyst of the oxygen reduction reaction (ORR) in MFCs. Yet the high cost of an MFC is mainly due to the high price of Pt. This, in turn, could deter the commercial MFC applications. So, the development of new materials with high catalytic properties to perform oxygen reduction is presently a task of great importance [2-5].

Some authors have reported [6-8] that Ru-chalcogenide (Ru–Se) compounds exhibit faster ORR kinetics compared to pure Ru electrocatalyst in polymer electrolyte membrane fuel cells (PEMFC). This result has been attributed to the role of selenium which presumably acts as an oxygen adsorption site, promoting the electron transfer between the carbon support and the catalytic center (Ru).

This mechanism is thought to protect the catalyst from the formation of inactive ruthenium oxide, making the ruthenium–selenide base material stable against the corrosive environment within the fuel cell [6,9-11]. The $\text{Ru}_x\text{Mo}_y\text{Se}_z$ electrocatalyst synthesized in 1,6-hexanediol has demonstrated catalytic activity for oxygen reduction in acid medium and as a cathode in a single PEMFC [12,13]. The physical characterization of the synthesized catalyst showed nanometric particles with average crystallites around 2.8 ± 0.2 nm, comprised in an amorphous face. The best performance of the membrane electrode assembly (MEA) was reached with a cathode catalyst loading of $1\text{ mg}/\text{cm}^2$ of $\text{Ru}_x\text{Mo}_y\text{Se}_z$ 20wt% dispersed in Carbon Vulcan XC-72 and anodic loading of $0.8\text{ mg}/\text{cm}^2$ Pt 10wt%/C (E-TEK). The associated results were $240\text{ mW}/\text{cm}^2$ at 0.30V . This value is nearly half of the performance obtained with Pt under the same pressure and temperature conditions. Results of membrane-electrode assembly MEA performance shows that $\text{Ru}_x\text{Mo}_y\text{Se}_z$ catalyst could be used in low power PEMFC devices. Meanwhile, the catalytic activity of the ruthe-

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ABBREVIATIONS

<i>ABS-MFC</i>	anaerobic baffled stacking microbial fuel cell
<i>ANOVA</i>	analysis of variance
<i>COD</i>	chemical oxygen demand
<i>E_{MFC-OCP}</i>	open circuit potential of the cell
<i>MEA</i>	membrane-electrode assembly
<i>MFC</i>	microbial fuel cell
<i>MFC-C</i>	two-face single chamber microbial fuel cell with two sandwich electrode with either chalcogenide catalyst and Pt in the cathode
<i>MFC-P</i>	five face parallelepiped MFC with sandwiched electrodes in each face
<i>MFC-T</i>	new design of a single chamber microbial fuel cell with triangular pieces of graphite as anode and either chalcogenide catalyst or Pt in the cathode
<i>PEM</i>	proton exchange membrane
<i>PEMFC</i>	polymer electrolyte membrane fuel cell
<i>P_{S-max}</i>	maximum power density (superficial)
<i>P_{V-max}</i>	maximum volumetric power
<i>R_{int}</i>	internal resistance
<i>SCS-MFC</i>	single chamber attackable microbial fuel cell
<i>SR-In</i>	sulphate-reducing inoculum
<i>VSS</i>	Volatile suspended solid
<i>Greek characters</i>	
ξ	ratio of electrode surface (typically the anode) to cell volume

nium-based catalyst for the ORR and *MEA* preparation techniques should be improved to attain at least the same performance as reached with Pt-based electrocatalysts [12].

One of the challenges in microbial fuel cells research consists of the application of new electrochemically active catalytic materials (such as $\text{Ru}_x\text{Mo}_y\text{Se}_z$ [12,13]) as alternative electrocatalysts to replace the extensive use of the more expensive platinum. Yet, to the best of our knowledge, there is no information in the open literature regarding the use of Ru chalcogenide as cathode electrocatalysts in microbial fuel cells.

On the other hand, search on anode materials has received great attention in order to further increase the power output of microbial fuel cells. A good anode material should have the following properties [14-16]: (*i*) good electrical conductivity and low resistance; (*ii*) strong biocompatibility; (*iii*) good chemical stability and high corrosion resistance; (*iv*) large surface area; and (*v*) appropriate mechanical strength and toughness. Common anodic materials in lab scale *MFCs* include a large variety of carbon materials and several

metals, which vary greatly in configurations and surface area. The carbon paper [17], graphite plates [18] and carbon cloth [1,16,19] are the most common materials for plain electrodes [20]. These materials have compact structure and relatively smooth surface, both of which facilitate the quantitative measurement of biomass per unit of surface area [20]. However, their low specific area, porosity and high cost inhibit the application of these electrodes in large-scale *MFCs* [20,21]. One way to increase the anode surface area has been through the use of particulate graphite such as granules [22,23].

Therefore, the objectives of our work were to evaluate (*i*) the application of $\text{Ru}_x\text{Mo}_y\text{Se}_z$ as cathode chalcogenide catalyst for oxygen reduction reaction (ORR), and (*ii*) the effect of two anodic materials on the performance of two microbial fuel cells (*MFCs*).

2. MATERIALS AND METHODS

2.1. Microbial fuel cell architecture

The *MFC-C* (Figure 1a) consisted of a horizontal cylinder built in Plexiglass 78 mm long and 50 mm internal diameter, according to what was reported elsewhere [9]. In summary, in the *MFC-C*, the two circular, opposing faces of the cylindrical shell were fitted with corresponding sets of an assemblage or circular “sandwich” arrangement that consisted (from inside to outside) of an anode made of Toray carbon cloth, the proton exchange membrane (Nafion 117), and a cathode made of flexible carbon-cloth containing either $1 \text{ mg/cm}^2 \text{ Ru}_x\text{Mo}_y\text{Se}_z$ (20%w/w Vulcan carbon) or 0.5 mg/cm^2 platinum catalyst (Pt 10 wt%/C-EETEK), and a perforated plate of stainless steel 1 mm thickness. This “sandwich” arrangement is referred to as *AMC* for the anode-membrane (PEM)-cathode. Electrode separation was 7 cm. The anode chamber volume was 150 mL and the anode surface area was 20 cm^2 .

On the other hand, the cell *MFC-T* (Figure 1b) consisted of a horizontal cylinder built Plexiglass 90 mm long and 57 mm internal diameter. The opposing faces of the cylindrical shell were fitted with corresponding sets of an assemblage of (inside to outside) proton exchange membrane (Nafion 117), a Toray flexible carbon-cloth containing $1 \text{ mg/cm}^2 \text{ Ru}_x\text{Mo}_y\text{Se}_z$ (20wt%/C) or 0.5 mg cm^{-2} platinum catalyst (Pt 10 wt%/C-EETEK), and a perforated plate of stainless steel 1 mm thickness. Each assemblage was corresponded with anodes made of 65 triangular pieces of graphite each (pieces dimensions $1.4 \times 1.8 \times 0.5 \text{ cm}$, side x height x thickness) and a graphite rod as collector (80 mm long and 5 mm diameter). The average separation between cathode-anode in *MFC-T* was 17.5 mm. The anode chamber volume was 147 mL. The wet volume of the anodic zone Face I and II was 48 mL, respectively, and the anode surface area was estimated at 317 cm^2 .

Thus, the values of ξ [1] were 26 and 529 m^{-1} for the cells C and T with carbon cloth and the graphite pieces, respectively. All the cathodes in both cells *MFC-C* and *MFC-T* were in direct contact with atmospheric air on the perforate metallic plate side. When the cathodic biocatalyst was the chalcogenide, the cathode had a loading of $1.0 \text{ mg/cm}^2 \text{ Ru}_x\text{Mo}_y\text{Se}_z$ 20 wt% dispersed in Vulcan carbon XC-72 as it was mentioned above. The catalytic ink was prepared by mixing $11.1 \mu\text{L}/\text{cm}^2$ Nafion® 5 wt% and $333.3 \mu\text{L}/\text{cm}^2$ of ethanol and the resulting suspension was sprayed onto the PEM of a home fabricated electronic semiautomatic device. Afterwards, the PEM was pressed the by hot pressing (4.4 kg/cm^2) at 120°C for 3 min to improve adherence of catalyst to the membrane [12].

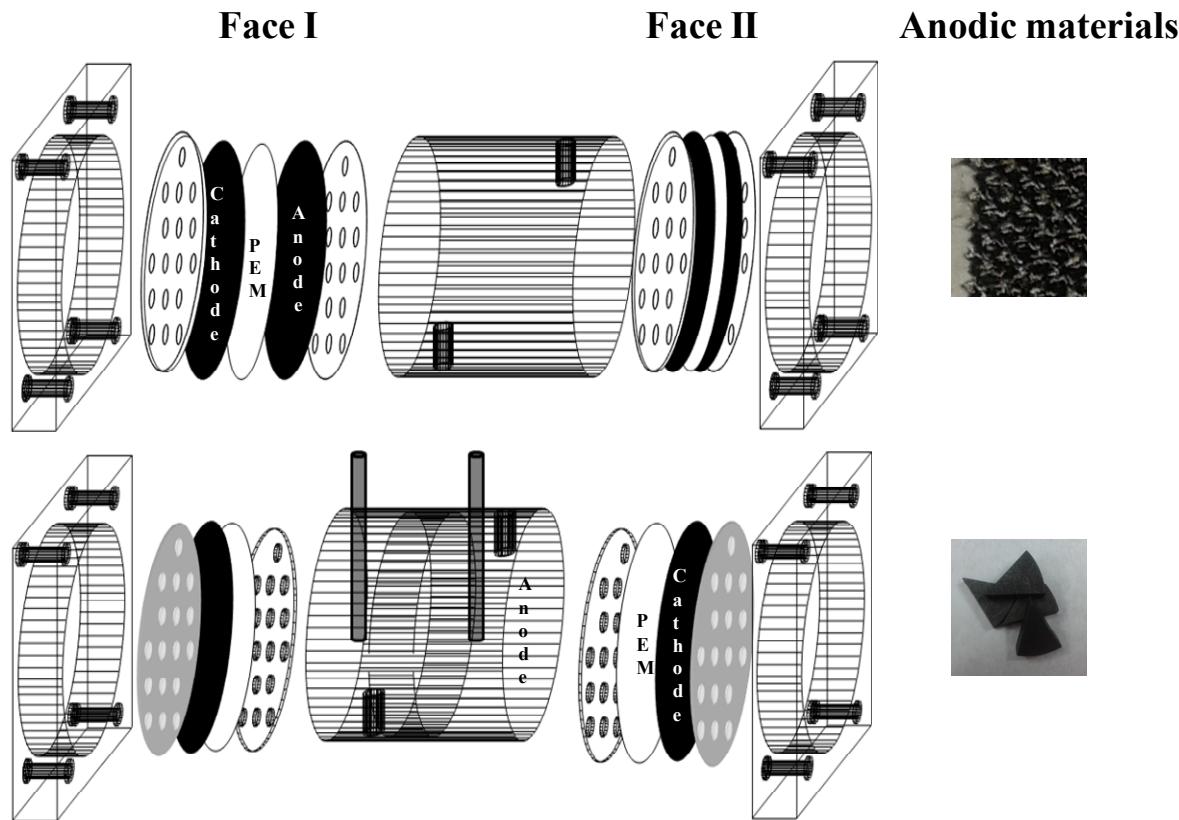


Figure 1. Schematic diagram a Microbial fuel cells: (a) *MFC-C* (materials electrodes carbon cloth in the anode and cathode) and (b) *MFC-T* (material electrodes carbon cloth in the cathode and triangular pieces of graphite).

2.2. Catalyst synthesis

The $Ru_xMo_ySe_z$ catalyst was synthesized by decarbonylation of transition-metal carbonyl compounds in organic solvent, under refluxing [24-26]. The $Ru_xMo_ySe_z$ catalyst was synthesized by reacting 0.07 mM $Ru_3(CO)_{12}$ (Aldrich) with 0.20 mM $Mo(CO)_6$ (Strem) and 0.20 mM of elemental selenium (Strem) in a chemical reactor containing 150 mL of 1,6-hexanediol for 3 hours at 230 °C. The un-reacted precursors and the organic reaction medium were eliminated by several washes using organic solvents, and dried overnight at room temperature [12,13].

2.3. Physical characterization

The catalyst was composed of uniform agglomerates of nanocrystalline particles with an estimated composition of $Ru_6Mo_1Se_3$, embedded in an amorphous phase. Tafel slopes for the ORR remained invariant with temperature at -0.116 V dec^{-1} with an increase of the charge transfer coefficient in $d\alpha/dT = 1.6 \times 10^{-3}$, ascribed to an entropy turnover contribution to the electrocatalytic reaction. The apparent activation energy was 45.6 ± 0.5 kJ mol $^{-1}$. The catalyst generated less than 2.5% hydrogen peroxide during oxygen reduction.

2.4. Experimental design

2.4.1. Experimental design and microbial fuel cells

The experiment was carried out as a factorial design with factor 'type of anodic material' (carbon cloth and triangular pieces graph-

ite) and factor 'type of catalyst' ($Ru_xMo_ySe_z$ and Pt), each factor at two levels or 2^2 [27]. The main variable responses were the internal resistance of the *MFC* and the maximum volumetric power P_{V-max} as reported by Vazquez-Larios *et al.* [28]. Results were further processed by analysis of variance (ANOVA) corresponding to the factorial 2^2 , in order to assess the statistical significance of the main effects and interaction of factors [27].

2.4.2. Model Extract and Biocatalysts

The cells were loaded with 7 ml of a model extract similar to the leachate found in the biological hydrogen production from the organic fraction of the municipal solid wastes [16,29-32]. The model extract was concocted with a mixture of the following substances (in g/L): acetic acid (1.4), propionic acid (0.3) and butyric acid (0.2) as well as acetone (0.04) and ethanol (0.08) and mineral salts such as $NaHCO_3$ and Na_2CO_3 (3 each) and K_2HPO_4 and NH_4Cl (0.6 each). Organic matter concentration of model extract was *ca.* 35 g COD/L. The cells were also loaded with 143 mL of mixed liquor from a sulphate-reducing, mesophilic, complete mixed, continuous bioreactor. The bioreactor had an operation volume of 3 L and was operated at 35°C in a constant temperature room. The bioreactor was fed at a flow rate of 120 mL/d with an influent whose composition was (in g/L): sucrose (5.0), acetic acid (1.5), $NaHCO_3$ (3.0), K_2HPO_4 (0.6), Na_2CO_3 (3.0), NH_4Cl (0.6), plus sodium sulphate (13.0). The initial chemical oxygen demand

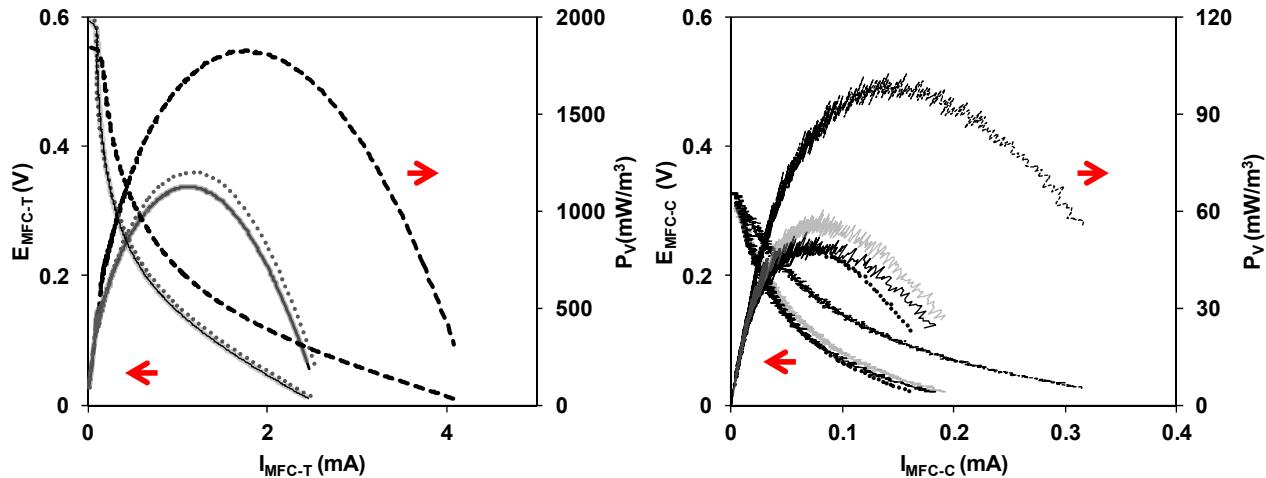


Figure 2. Curves of polarization: (a) MFC-T and (b) MFC-C (-, face I; -, face II; .., series and --, parallel) and volumetric power (-, face I; -, face II; .., series and --, parallel) of microbial fuel cells using a sulphate-reducing and $\text{Ru}_x\text{Mo}_y\text{Se}_z$ catalyst.

(COD) and biomass concentration expressed as volatile suspended solid (VSS) in the cell liquor were *ca.* 1 250 mg O₂/L and 890 mg VSS/L, respectively. Molecular biology studies were performed to determine inoculum composition. It was found that bacterial members of the biofilm of the MFC loaded with SR-In were *Clostridia* (42%), 98% identity with *Clostridiales bacterium*; δ -*Proteobacteria* (16%), 99% identity with *Desulfovibrio desulfuricans*; *Firmicutes* (16%), 96% identity with *Alkaliphilus oremlandii*, and an *Uncultured bacterium* (26%) 93% identity with *uncultured bacterium* [33]. Ecological indices suggested that inoculum diversity and evenness were moderate.

2.4.3. Electrochemical and analytical methods

Potential sweep experiments were carried out from open-circuit cell voltage (E_{OCP}), to the final potential of 0.02 V at a scan rate of 1mV/s, performed in a potentiostat/galvanostat Voltalab model PGZ402 [34,35]. Values of R_{int} were estimated from the slopes of corresponding regression lines selected in the linear range of the polarization curves. The current (I_{MFC}), power (P_{MFC}) and volumet-

ric power (P_V) were calculated as previously described [36]. The power density was normalized to the projected cathode surface area (surface power density P_{S-max}). The COD and VSS of the liquors of sulphate-reducing seed bioreactor and cells were determined according to the Standard Methods [37]. In addition, the individual concentrations of volatile organic acids and solvents in the model extract were analyzed by gas chromatography in a chromatograph Perkin Elmer Autosystem equipped with a flame ionization detector as described elsewhere [29].

3. RESULTS AND DISCUSSION

The first set of experiments consisted of the application of $\text{Ru}_x\text{Mo}_y\text{Se}_z$ as a cathodic catalyst for ORR in the *MFC-T* (cell equipped with triangular pieces of graphite as anode) and *MFC-C* (anode made of flexible carbon-cloth) (Table 1). Each face (I and II) of the *MFC-T* and *MFC-C* was characterized by separate (I and II), in series, and parallel electric arrangements (Figure 2a,b).

Parallel connection of faces increased P_{V-max} up to 1739 and 102 mW/m³ values for *MFC-T* and *MFC-C*, respectively, compared

Table 1. Effect of the type of anodic material on characteristics of MFC-T and MFC-C with different connections of their two faces (electrodes) and $\text{Ru}_x\text{Mo}_y\text{Se}_z$ cathodic catalyst

Type cell	Type connection	$E_{MFC,OCP}$ (V)	P_{S-max} (mW/m ²)	P_{V-max} (mW/m ³)	$R_{int} [R^2]$ (Ω)
MFC-T Anode: graphite triangular pieces	Face I	0.591	53.0	1142	146 [0.94]
	Face II	0.593	49.5	1067	167 [0.93]
	Series ^a	0.628	22.8	983	162 [0.93]
	Parallel ^b	0.506	40.4	1739	69 [0.99]
MFC-C Sandwich electrodes with carbon cloth anode	Face I	0.332	4.0	51	1 612 [0.95]
	Face II	0.311	4.4	56	1 397 [0.96]
	Series ^a	0.313	1.8	47	1 874 [0.98]
	Parallel ^b	0.308	4.0	102	820 [0.95]

^a the two facial electrodes were connected in series; ^b the two facial electrodes were connected in parallel; MFC-T, new design of single chamber cell; $E_{MFC-OCP}$, open circuit potential; P_{S-max} , maximum power density; P_{V-max} , maximum volumetric power; R_{int} , internal resistance; R^2 , determination coefficient

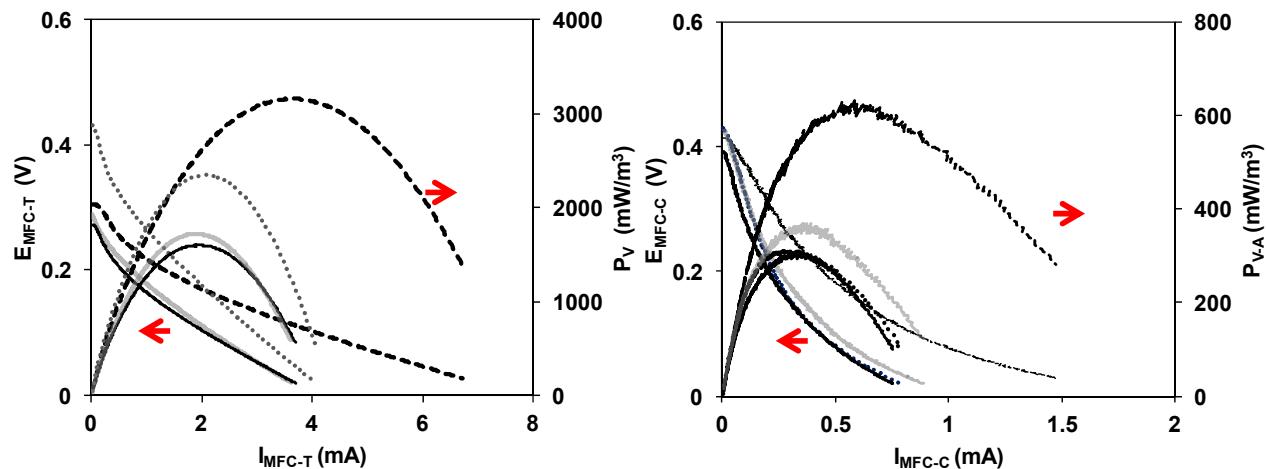


Figure 3. Curves of polarization: (a) MFC-T and (b) MFC-C (-, face I; -, face II; .., series and --, parallel) and volumetric power (-, face I; -, face II; .., series and --, parallel) of microbial fuel cells using a sulphate-reducing and Pt catalyst.

with 1142 and 1067 mW/m³ for face I and face II by separate (*MFC-T*) and 51 and 56 mW/m³ for face I and face II by separate (*MFC-C*). Parallel connection significantly decreased the R_{int} of the cells and almost doubled volumetric power for *MFC-T* and *MFC-C*, respectively. The $P_{V,max}$ for the *MFC-T* when faces were connected in series and parallel were higher than that reported by Ortega-Martinez *et al.* [33], when characterizing a novel, multi-face parallelepiped *MFC* (Pt for ORR). This cell was fitted with a ‘sandwich’ cathode-membrane-anode assemblage in five of their faces. When the 5 faces of the *MFC-P* were connected in series and parallel, the $P_{V,max}$ achieved values of 62 and 570 mW/m³, respectively.

Our values of $P_{V,max}$ for individual faces were comparable with those reported by Zhong *et al.* [38]. They experimented with an anaerobic baffled stacking microbial fuel cell (*ABS-MFC*) that consisted of four units; a molasses wastewater was the fuel. They observed that the maximum power densities for each unit (152 mW/m² and 1 330 mW/m³) were 31.6% higher than the average value (115.5 mW/m² or 1 010 mW/m³) of the four units. The R_{int} of

unit 1 and unit 3 (150.9 and 141.7 Ω) were lower than the internal resistance of unit 2 and unit 4 (208.0 and 211.4 Ω), these values were similar to those obtained in our work.

The increment of $P_{V,max}$ for our *MFC-T* could be attributed to the increase of the total electrode surface area by the application of triangular pieces of graphite, and this, in turn, could have improved the electron transfer microbe-to-anode process [38]. Also, our work demonstrated that parallel connection of cell faces was more appropriate regarding electrochemical characteristics of cells than series connection.

Afterwards, we tested the cells using Pt as cathodic catalyst for RRO (Table 2). First each face of the *MFC-T* and *MFC-C* was characterized by separate face (I and II). Second, the *MFCs* was characterized with the two faces connected in series and parallel (Figure 3a,b).

The $P_{V,max}$ values were 3 098 and 547 mW/m³ for parallel connection of faces in the *MFC-T* and *MFC-C*, respectively. The corresponding internal resistances were 33 and 257 Ω (Table 2). The power output of *MFC-T* was high and comparable with the values

Table 2. Effect of the type of anodic material on cell characteristics *MFC-T* and *MFC-C* with different connections of their two faces (electrodes) and Pt cathodic catalyst.

Type cell	Type connection	$E_{MFC,OCP}$ (V)	$P_{S,max}$ (mW/m ²)	$P_{V,max}$ (mW/m ³)	$R_{int} [R^2]$ (Ω)
MFC-T Anode: graphite triangular pieces	Face I	0.276	73.2	1577	55 [0.99]
	Face II	0.325	75.8	1633	62 [0.99]
	Series ^a	0.432	56.0	2094	83 [0.99]
	Parallel ^b	0.309	71.9	3098	33 [0.99]
MFC-C Sandwich electrodes with carbon cloth anode	Face I	0.429	21.1	266	429 [0.98]
	Face II	0.425	24.5	309	425 [0.98]
	Series ^a	0.431	11.2	442	589 [0.98]
	Parallel ^b	0.414	21.6	547	257 [0.96]

^a the two facial electrodes were connected in series; ^b the two facial electrodes were connected in parallel; MFC, new design of single chamber cell; $E_{MFC,OCP}$, open circuit potential; $P_{S,max}$, maximum power density; $P_{V,max}$, maximum volumetric power; R_{int} , internal resistance; R^2 , determination coefficient.

reported in the literature [38,39].

The R_{int} decreased in the parallel connection of the faces of cells. This was in agreement with results reported elsewhere [38]. In this research, it was tested the effect of method of connection on power generation in an ABS-MFC; the authors connected the four units in series or parallel using copper wires. Their results showed that parallel connection decreased the R_{int} of the cell to a low value (45 Ω). The $P_{V\text{-max}}$ for parallel and series connection were 1 268 and 942 mW/m³ respectively, and these values were lower than those obtained in this work with our MFC-T.

The $P_{V\text{-max}}$ and R_{int} in our Pt- MFCs were lower and comparable, respectively, with corresponding values observed by Wang & Han [40]. They evaluated a single chamber stackable microbial fuel cell (SCS-MFC) comprising four MFC units. When operated separately, each unit generated a $P_{V\text{-max}}$ of 2 860 mW/m³ (51.3 Ω). Series connection of two units, however, only generated a 5760 mW/m³ (121 Ω) whereas parallel connection produced a 6 500 mW/m³ (31.3 Ω). In their work, parallel connection significantly decreased the internal resistance of both cells (33 Ω) and almost doubled volumetric powers (Table 2). The internal resistance values in this work were in the low side of the range reported in the literature [38].

In our work, in general, series connection of faces did not lead to an increase of the voltage output, as it was expected based on the simple Ohm's law. This was in agreement with several previous studies [41-44]. One approach to increase MFC voltages would be to connect multiple MFC in series, forming a stacked system. However, when this is done the stack usually undergoes voltage reversal, resulting in a lower or nearly zero stack voltage. Voltage reversal has been shown to occur when anode potentials become unbalanced, for example when substrate concentration are low in one cell relative to an adjacent cell. In this scenario, the bacteria are less active at the lower substrate concentration; as a result, the anode potential of that cell becomes positive and similar to the cathode potential of the adjacent cell. Moreover, voltage reversal can also occur under high current even without substrate depletion. Voltage reversal occurring in only one of multiple MFCs connected in series generally results in a failure of the whole system [41-44].

The relatively low values of $P_{S\text{-max}}$ obtained in this work could be due to lack of acclimation of the inoculum to the new substrate. The microbial consortium in the sulphate-reducing inoculating bioreactor was acclimated to a substrate that consisted of sucrose and acetic acid, as well as sodium sulfate as electron acceptor. After transferring the inoculum to the MFC, the substrate fed was a model extract that neither contained sucrose nor sulphate (the substrate was a mixture of acetic, propionic and butyric acids as well as acetone and ethanol and mineral salts.) That is, the absence of acclimation to the new substrate could have played a negative effect on MFC performance. Furthermore, the inoculum was not previously enriched for electrochemically-active bacteria (also known as anodophilic or exoelectrogenic bacteria). As it is known, most of these microorganisms are dissimilatory metal reducing microorganisms, and their presence and predominance in the consortia anchored in MFCs are associated to high power outputs [1,45, 28,46-49].

The values of $P_{V\text{-max}}$ obtained in our experiment were subjected to an ANOVA according to a factorial design 2², in order to assess its statistical significance. Both the factors 'type of anodic material' (carbon cloth and triangular pieces graphite), and 'type of catalyst'

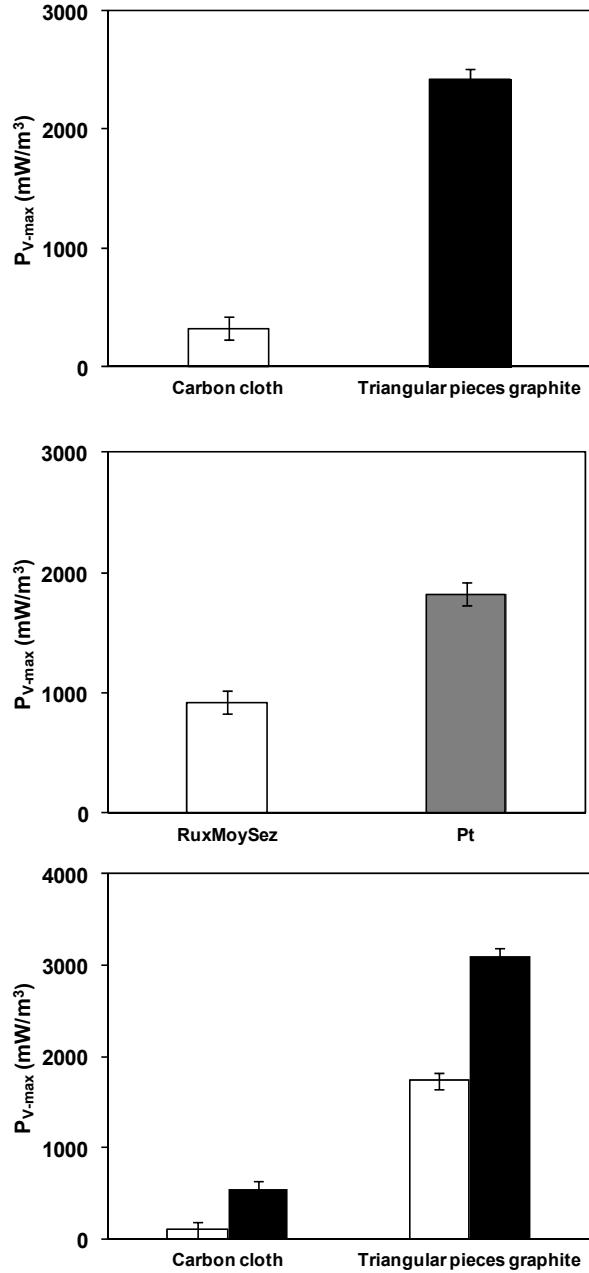


Figure 4. Main effects of factors (a) type of anodic material; (b) catalyst type and (c) interaction factors on the maximum volumetric power ($P_{V\text{-max}}$). The error bars correspond to the error of the experimental design (EED), calculated as $EED = (MSE/r)^{1/2}$ where MSE stands for mean of the sum of squares of the error, and r is the number of replicates (r = 2).

(Ru_xMo_ySe_z and Pt) as well as their interaction were significant (Figure 4a,b,c) with probability values < 0.0001, 0.0002 and 0.0028, respectively. Results statistically confirmed that the new cell design MFC-T was associated to the highest $P_{V\text{-max}}$ values.

The effect of "type of catalyst" interaction was significant and the ANOVA statistically confirmed that Pt was associated to high $P_{V\text{-max}}$ values. Indeed, the power with Ru calcogenide was 57% of

that obtained with Pt. The relationship of powers delivered by cells fitted with the catalysts was similar to that reported by Zhong et al. [38] in their experiment with a lab scale proton-exchange membrane microbial fuel cell (PEMFC) fed with hydrogen (chemical cell). In effect, they observed a maximum power of 450 mW/cm^2 with Pt catalysts whereas the maximum value for Ru chalcogenide was 250 mW/cm^2 , that is, the second was 56% of the first one. So, the performance of Ru chalcogenide in our MFC followed the same pattern as the performance in chemical fuel cells, regarding the use of Pt.

Moreover, at this point, a cost-benefit discussion on the use of both catalysts is advisable. In this work, the preliminary cost estimated for $Ru_xMo_ySe_z$ was US\$ $4/\text{cm}^2$ as compared with US\$ $15.7/\text{cm}^2$ of the Pt/C based cathode catalyst, based on US\$ $31.64/\text{g}$ and US\$ $2.63/\text{g}$ of Ru calcogenide and Pt, respectively [12]. In this work, the preliminary cost estimated for $Ru_xMo_ySe_z$ was US\$ $4/\text{cm}^2$ as compared with US\$ $15.7/\text{cm}^2$ of the Pt/C based cathode catalyst, based on US\$ $31.64/\text{g}$ and US\$ $2.63/\text{g}$ of Ru calcogenide and Pt, respectively [12]. We have made a preliminary estimation of the catalyst costs based on the prices and proportions of the reagents required to form the catalyst in each case. Platinum of purity 99.99% was quoted, whereas for the chalcogenide catalyst, the costs of reagents corresponded to chemical pure compounds. Labor costs were not taken into account. If we compare the catalyst estimated cost ratio with the delivered power ratio, it is easy to confirm that Ru chalcogenide has a more cost effective (ratio of costs $4/15.7 = 0.26$; ratio of powers $1\ 739/3\ 098 = 0.57$). That is, power delivered by the cell with Ru chalcogenide is 57%, whereas the cost per cm^2 of cathode is just 27% of that of the cell with Pt.

4. CONCLUSION

The MFC-T equipped with anodic triangular graphite pieces showed higher values of $P_{V\text{-max}}$ and significant lower internal resistances than the cell C with sandwich electrodes and anodic carbon cloth.

On the other hand, the power output of by cell T with cathodic chalcogenide catalyst was 43% inferior to that of a similar cell with Pt although the cost of the first catalyst is significantly lower (73%) than that of Pt. The lower power harvested using chalcogenide catalyst is easily offset by the savings associated to Pt replacement.

Our results have demonstrated the promising application of graphite anode made of small triangular pieces on performance of a MFC-T that used $Ru_xMo_ySe_z$ as a cathodic catalyst for oxygen reduction reaction.

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