CHAPTER 5
The Promotional Roles of Ru and Rh in Carbon-Supported Pt–Ru, Pt–Rh, and Pt–Ru–Rh Catalysts Toward Methanol Electro-Oxidation

Abstract

In the present work, carbon-supported \( \text{Pt}_{50}\text{Ru}_{25}\text{Rh}_{25} \), \( \text{Pt}_{50}\text{Ru}_{50} \), and \( \text{Pt}_{50}\text{Rh}_{50} \) electrocatalysts were synthesized by co-impregnation reduction method. The physicochemical characterizations demonstrated that all the compositions have the Pt face-centered cubic (fcc) structure with variations in the lattice parameter, indicating the incorporation of Ru and Rh. TEM measurements revealed a decrease in the mean particle size of the catalysts for the ternary compositions. The electrochemical characterization showed that binary and ternary electrocatalysts have higher catalytic activity than Pt/C toward methanol electro-oxidation. Voltametric data showed that the addition of Rh to Pt–Ru/C significantly diminished the potential of methanol and CO oxidation as a result of the electronic effect exerted by this metal along with the bifunctional mechanism. Single cell tests on a membraneless methanol fuel cell at room temperature with \( \text{Pt}_{50}\text{Ru}_{25}\text{Rh}_{25} \)/C demonstrated superior performance as compared to \( \text{Pt}_{50}\text{Ru}_{50} \)/C, \( \text{Pt}_{50}\text{Rh}_{50} \)/C, and Pt/100/C electrocatalysts. The i-V characteristic curve indicated an enhancement in the fuel cell performance with the addition of Rh and Ru to the Pt-catalyst.

5.1 Introduction

The need for more efficient energy conversion systems is presently in great evidence as the world fossil fuel sources become depleted. Fuel cells have proved to be an interesting and very promising alternative to solve the problem of clean electric power generation with high efficiency (Wendt et al., 2000).
Methanol has been considered as an alternative to hydrogen for fuel cell applications since it is a liquid at room temperature thus makes the handling and storage much easier than in the case of hydrogen. At room, the use of pure platinum as a catalyst for methanol electrooxidation is not very appropriate because it is readily poisoned by strongly adsorbed CO intermediates. It has been shown that the combination of Pt with a second or a third component is a convenient way to modify the electrocatalytic properties of this metal (Peled et al., 2001). Therefore, various Pt-based binary catalysts such as Ru, Sn, Mo, W, Os, Rh, Co, and Ni have been intensively investigated with the view of enhancing the catalytic activity by eliminating or inhibiting the CO poisoning effect on the basis of a bifunctional mechanism or an electronic effect (Ishikawa et al., 2000; Sung et al., 2000; Park et al., 2002). Although it is known that Pt–Ru/C is the best catalyst for methanol electrooxidation, considerable effort continues to be focused on the development of new ternary or quaternary alloy catalysts (Lima et al., 2001; Choi et al., 2003). The goal of this study was to evaluate the catalytic activity for methanol oxidation reaction (MOR) by incorporating Rh to Pt–Ru/C catalysts in MLMFC.

5.2 Experimental

5.2.1 Materials

The metal precursors used for the preparation of electrocatalysts were H₂PtCl₆·6H₂O (from Sigma Aldrich), RuCl₃·3H₂O (from Sigma Aldrich) and RhCl₃ (from Sigma Aldrich). Vulcan XC-72R carbon black (from Cabot Corp.,) was used as a support for the catalysts. Graphite plates (from E-TEK) were used as substrates for the catalyst to prepare the electrodes. Nafion® (DE 521, DuPont USA) dispersion was used to make the catalyst slurry. Iso-propanol (from Merck) was used as a solvent and NaBH₄ (from Merck) was used as the reduction agent. Methanol (from Merck), sodium perborate (from Riedel) and H₂SO₄ (from
Merck) were used as the fuel, the oxidant and as the electrolyte for electrochemical analysis, respectively. All the chemicals were of analytical grade. Pt/C (40-wt%, from E-TEK) was used as the cathode catalyst.

5.2.2 Catalyst Preparation

Carbon supported ternary Pt–Ru–Rh catalysts with different atomic ratios were synthesized by co-impregnation reduction method (Zhou et al., (2004)). The precursors were first suspended in iso-propanol and ultrasonicated for 3h. The carbon support Vulcan XC-72R, was preheated to 110 °C for 2h and suspended in iso-propanol separately and ultrasonicated for 3h. Precursor suspension is then added drop wise to carbon slurry. The weight ratio of Pt–X/C (X = Ru, Rh, Ru–Rh) was controlled according to the targeted metal loading. Ultrasonic blending for 3h, of precursor and carbon suspension was carried out to ensure the proper impregnation of metal precursors on carbon support. The suspension was then kept at 70 °C for 12h to evaporate iso-propanol. To reduce metal precursors 0.2 M NaBH₄ solution was added to the mixture with stirring and further stirred for 3h to confirm termination of reduction reaction. Finally the precipitate was collected by filtration, washed with ultrapure water (Millipore MilliQ, 18 MΩ cm), and dried at 70 °C for 2h. The electrocatalytic mixtures and atomic ratios were Pt₁₀₀Ru₂₅Rh₂₅/C, Pt₅₀Ru₅₀/C, Pt₅₀Rh₅₀/C, and Pt₁₀₀/C. The nominal loading of metals in the electrocatalysts was 40 %wt and rest 60 %wt was carbon.
5.3 Results and Discussions

5.3.1 Physical Characterization

5.3.1.1 X-ray Diffraction (XRD)

Fig. 5.1 shows the diffraction patterns for the prepared Pt_{50}Ru_{25}Rh_{25}/C, Pt_{50}Ru_{50}/C, Pt_{50}Rh_{50}/C and Pt_{100}/C electrocatalysts.

![X-ray diffraction patterns of Pt_{50}Ru_{25}Rh_{25}/C, Pt_{50}Ru_{50}/C, Pt_{50}Rh_{50}/C, and Pt_{100}/C catalysts](image)

In all cases, XRD patterns exhibit 2θ values of 39°, 47°, 67° and 82° and are indexed with planes (1 1 1), (2 0 0), (2 2 0) and (3 1 1), respectively. In the case of Pt–Rh/C, the diffraction peaks are slightly shifted to higher angles of 2θ with respect to those of Pt/C electrocatalyst, indicating a lattice contraction and alloy formation. No peaks due to metallic Rh or to their oxides were observed. On the other hand, results for the Pt–Ru/C and Pt–Ru–Rh/C electrocatalysts show no shift of the diffraction angles and some segregation of metallic Ru. This is evidenced by the diffraction peaks originated from the hexagonal structure of Ru atoms, which is more pronounced for the Pt–Ru/C electrocatalyst, as indicated in the figure.
As the diffraction signals for the Pt–Ru/C and Pt–Ru–Rh/C catalysts have some overlap with the signals from the Ru hexagonal phase, the calculated crystallite sizes for these two materials are only approximated. It can be observed that the electrocatalysts are nanostructured, and the Pt–Rh/C material presenting the larger size (Lima et al., 2008). This may be associated to a favored growth during the catalyst preparation due to the alloy formation.

The lattice parameters evaluated from the angular position of the (2 2 0) peaks were gradually decreased with an increase in the Rh content showing that the extent of alloying of these ternary alloy particles are not perfect but considerably well alloyed. The lattice parameters obtained for Pt–Rh/C (0.3884 nm), Pt–Ru/C (0.3903 nm) and Pt–Ru–Rh/C (0.3902 nm) catalysts are smaller than those for Pt/C electrocatalyst (0.3915 nm) (Table 6.1).

Table 5.1 The EDX composition, lattice parameters, and the particle size obtained for different atomic ratios of electrocatalysts

<table>
<thead>
<tr>
<th>Electro催化剂</th>
<th>Nominal Atomic ratio</th>
<th>EDX Atomic ratio</th>
<th>Lattice parameter (nm)</th>
<th>Crystallite size (nm)</th>
<th>Particle size from TEM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt/C</td>
<td>100 - - 99 -</td>
<td>0.3915</td>
<td>4.5</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Pt–Rh/C</td>
<td>50 - 50 51 - 49</td>
<td>0.3884</td>
<td>4.3</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Pt–Ru/C</td>
<td>50 50 - 52 48 -</td>
<td>0.3903</td>
<td>3.6</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Pt–Ru–Rh/C</td>
<td>50 25 25 52 24 24</td>
<td>0.3902</td>
<td>3.2</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

The average particle size for Pt–Ru/C, Pt–Rh/C and Pt–Ru–Rh/C electrocatalysts were in the range of 3-5 nm was estimated using the Scherrer equation are in good agreement with the TEM images.
5.3.1.2 Transmission Electron Microscopy (TEM)

TEM image of the Pt$_{50}$Ru$_{25}$Rh$_{25}$/C alloy catalysts and the corresponding particle size distribution histogram are presented in Fig. 5.2.

![TEM image and particle size distribution of Pt$_{50}$Ru$_{25}$Rh$_{25}$/C catalyst](image)

From the TEM image, the average particle diameter was found to be approximately 3-5 nm, which is in fairly good agreement with the data calculated from XRD. The particle size distribution of these catalysts is shown in Table 5.1 in accordance to the TEM images.

5.3.1.3 Energy Dispersive X-ray Spectroscopy (EDX)

Energy dispersive X-ray spectroscopy is conducted by focusing the electron beam on several different selected regions of the carbon supported nanoparticles. An EDX spectrum of Pt–Ru–Rh/C nanoparticles is shown in Fig. 5.3. The average composition of the sample was in atom ratio of Pt:Ru:Rh = 2:1:1. The EDX result of the ternary Pt–Ru–Rh/C catalysts is very close to the nominal values, which indicate that the metals were loaded onto the carbon support without obvious loss.
Fig. 5.3 EDX spectra of Pt–Ru–Rh/C electrocatalysts

5.3.2 Electrochemical Characterization

5.3.2.1 Cyclic Voltammetry

Fig. 5.4a shows the cyclic voltammograms obtained at a scan rate of 50mVs$^{-1}$ for the Pt–Ru/C and Pt–Rh/C binary alloys and for the Pt–Ru–Rh/C ternary alloy, compared to that for Pt/C.

Fig. 5.4a CVs of Pt$_{50}$Ru$_{25}$Rh$_{25}$/C, Pt$_{50}$Ru$_{50}$/C, Pt$_{50}$Rh$_{50}$/C and Pt$_{100}$/C electrocatalysts in 0.5 M H$_2$SO$_4$
The currents are normalized by total surface area, obtained by CO stripping. The results show the typical behaviour regarding the hydrogen and the oxide regions of Pt in the electrocatalysts in acid solutions (Paulus et al., 2002). In the case of Pt–Ru/C, a large value of the double-layer charging current is observed, and this is attributed to the presence of Ru-oxides at the particle surface, increasing the electrode capacitance. The hydrogen region in the Pt–Ru/C material is also modified in comparison to that region for Pt/C or Pt–Rh/C, and this is due to the formation of oxygenated species on the Ru atoms (Gasteiger et al., 1994). In the case of the Pt–Rh/C alloy, the hydrogen adsorption/desorption profile is characterized by large single peaks (Gupta et al., 2006). Due to the strong adsorption of CO onto the Pt surface, the hydrogen adsorption-desorption of the Pt was completely blocked in the hydrogen region; indicating the presence of a saturated CO adlayer (Choi et al., 2003).

The electrochemically active surface areas (SEAS) of the electrocatalysts were calculated by using Eq. (5.1) (Zhou et al., 2003; Bonesi et al., 2010; Beyhan et al., 2013). SEAS values were estimated using hydrogen adsorption/desorption charge ($S_{EAS/H}$) and roughness of electrodes.

$$S_{EAS/H} (m^2/g) = \frac{Q_H(\mu C/cm^2)}{210(\mu C/cm^2) \times 0.77 \times [Pt]}$$

Where $Q_H$ is the charge corresponding to desorption of hydrogen on the Pt surface, $[Pt]$ (mg/cm$^2$) is the Pt loading on the electrode surface, 210 $\mu$C/real cm$^2$ is the charge required to oxidize a monolayer of hydrogen on the Pt surface, 0.77 is the hydrogen monolayer coverage (Biegler et al., 1971). The roughness of each electrode is calculated by dividing $S_{EAS}$ obtained with the apparent surface area. Estimation of the electrode roughness.
and $S_{EAS}$ values are shown in Table 5.2. Based on these values, the highest electrochemically active area is achieved for the ternary electrocatalysts.

### Table 5.2 Comparison of hydrogen desorption charge and carbon monoxide desorption charge, and its electrochemical active surface area ($S_{EAS}$) and electrode roughness

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>$Q_H/\mu C$</th>
<th>Electrode real surface area (cm$^2$)</th>
<th>$S_{EAS}$ ($m^2gPt^{-1}$)</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt$_{100}$/C</td>
<td>437</td>
<td>2.1</td>
<td>27</td>
<td>58.8</td>
</tr>
<tr>
<td>Pt$<em>{50}$Rh$</em>{50}$/C</td>
<td>243</td>
<td>1.2</td>
<td>30</td>
<td>33.6</td>
</tr>
<tr>
<td>Pt$<em>{50}$Ru$</em>{50}$/C</td>
<td>259</td>
<td>1.2</td>
<td>32</td>
<td>33.6</td>
</tr>
<tr>
<td>Pt$<em>{50}$Ru$</em>{25}$Rh$_{25}$/C</td>
<td>307</td>
<td>1.5</td>
<td>38</td>
<td>42.0</td>
</tr>
</tbody>
</table>

The CV curves were obtained in a half cell between 0.05 and 1.2 V (vs. Ag/AgCl) in the absence of methanol. The characteristic features of polycrystalline Pt, i.e. hydrogen adsorption/desorption peaks in low potential region, oxide formation/stripping wave/peak in high potential region and a flat double layer in between, are observed for all the synthesized catalysts. The voltammograms of the electrocatalysts did not display a well-defined hydrogen region between 0.05 and 0.35 V, as the catalyst’s features in this region are influenced by their surface composition. Taking the Pt$_{100}$/C composition as a reference, the binary Pt$_{50}$Ru$_{50}$/C and Pt$_{50}$Rh$_{50}$/C catalysts showed a voltammetric charge similar to that of the pure Pt catalyst. However, a considerable increase in the voltammetric charge of ternary Pt$_{50}$Ru$_{25}$Rh$_{25}$/C catalyst was observed in the double-layer region, indicating that the addition of Rh into binary Pt–Ru/C leads to an enhanced activity for the oxidation reactions. Thus, it can be concluded that the enhanced activity of Pt$_{50}$Ru$_{25}$Rh$_{25}$/C for methanol electrooxidation is mainly due to an intrinsic improvement in catalytic activity.
Fig. 5.4b corresponds to representative CVs of methanol oxidation under acidic conditions (1.0 M CH₃OH and 0.5 M H₂SO₄) catalyzed by Pt₅₀Ru₂₅Rh₂₅/C, Pt₅₀Ru₅₀/C, Pt₅₀Rh₅₀/C and Pt₁₀₀/C catalysts. The onset potential for the oxidation of methanol in a positive scan was a key factor for evaluating the catalyst activity (Cao et al., 2007).

The onset potentials for the oxidation of methanol on the Pt₅₀Ru₂₅Rh₂₅/C (0.21 V) electrocatalysts is slightly lower than that on the Pt₅₀Ru₅₀/C (0.30 V), Pt₅₀Rh₅₀/C (0.38 V) and Pt₁₀₀/C (0.45 V) catalysts. All the current values were normalized by the geometric surface area of the electrode used. The CV curves depict the presence of a peak in the potential range of the positive sweep and another peak in the negative sweep. The peak in the positive sweep is associated with the methanol oxidation, and the peak in the negative sweep is related to the oxidation of carbonaceous intermediate products from incomplete methanol oxidation. The peak current densities of Pt₅₀Ru₂₅Rh₂₅/C, Pt₅₀Ru₅₀/C, Pt₅₀Rh₅₀/C and Pt₁₀₀/C catalysts are 80.2, 49.7, 44.3 and 40.1 mA/cm², respectively, showing that the activity of the ternary
Pt₅₀Ru₂₅Rh₂₅/C catalyst is a factor of ~2 times higher than that of the Pt/C catalyst. Table 5.3 summarizes the CV results of Pt₅₀Ru₂₅Rh₂₅/C, Pt₅₀Ru₅₀/C, Pt₅₀Rh₅₀/C and Pt₁₀₀/C electrocatalysts including the positive peak potentials and the corresponding peak current densities of MOR.

Table 5.3 CV results of Pt₅₀Ru₂₅Rh₂₅/C, Pt₅₀Ru₅₀/C, Pt₅₀Rh₅₀/C and Pt₁₀₀/C electrocatalysts

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Positive peak potential (mV vs. Ag/AgCl)</th>
<th>Peak current density (mA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt₁₀₀/C</td>
<td>592</td>
<td>40.1</td>
</tr>
<tr>
<td>Pt₅₀Rh₅₀/C</td>
<td>534</td>
<td>44.3</td>
</tr>
<tr>
<td>Pt₅₀Ru₅₀/C</td>
<td>586</td>
<td>49.7</td>
</tr>
<tr>
<td>Pt₅₀Ru₂₅Rh₂₅/C</td>
<td>602</td>
<td>80.2</td>
</tr>
</tbody>
</table>

The CV results show that pure Pt₁₀₀/C catalysts do not behave as an appropriate anode for MOR due to its poisoning by strongly adsorbed intermediates such as CO. However, the introduction of Ru and Rh promotes the electrocatalytic activity. CV for methanol oxidation reactions showed that the CO poisoning effect was largely inhibited by Pt₅₀Ru₂₅Rh₂₅/C electrocatalysts, indicating the ability of Rh to promote either the CO to CO₂ oxidation or a weaker adsorption of CO on the Pt₅₀Ru₂₅Rh₂₅/C catalysts.

5.3.2.2 Chronoamperometry

Fig. 5.5 shows the current densities measured from 0.05 to 1.2 V in 1.0 M methanol+0.5 M H₂SO₄. The currents decay with time in a parabolic style and reach an apparent steady state within 80s. It can be seen that the current density of methanol
electrooxidation on the Pt_{50}Ru_{25}Rh_{25}/C catalyst is higher than that on the Pt_{50}Ru_{50}/C, Pt_{50}Rh_{50}/C and Pt_{100}/C catalyst at the same potentials.

Fig. 5.5 CA of Pt_{50}Ru_{25}Rh_{25}/C, Pt_{50}Ru_{50}/C, Pt_{50}Rh_{50}/C and Pt_{100}/C electrocatalysts

The activity change for methanol oxidation decreases in the order of Pt_{50}Ru_{25}Rh_{25}/C > Pt_{50}Ru_{50}/C > Pt_{50}Rh_{50}/C > Pt_{100}/C, which is in fairly good agreement with our CV results. For the durability test, the chronoamperometric experiments were carried out at 0.05 to 1.2 V for 1800 s in the same conditions. Before each measurement, the solution was purged with high-purity nitrogen gas for at least 30 min to ensure oxygen-free measurements.

5.3.3 Single Cell Performance

The microfluidic architecture of laminar flow-based membraneless fuel cells overcomes the fuel crossover and water management issues that plague membrane-based fuel cells (i.e., PEMFC, DMFC) and enables independent control of stream characteristics (i.e., flow-rate and composition). Here we focused on maximizing cell performance, in terms of power density, by tailoring various structural characteristics and catalytic activity of carbon
supported ternary Pt–Ru–Rh catalysts. A single cell performance was tested using 
Pt_{50}Ru_{25}Rh_{25}/C, Pt_{50}Ru_{50}/C, Pt_{50}Rh_{50}/C and Pt_{100}/C electrocatalysts as the anode. Polarization 
curves and power densities are shown in Fig. 5.6.

![Fig. 5.6 Polarization and power density curves of Pt_{50}Ru_{25}Rh_{25}/C, Pt_{50}Ru_{50}/C,
Pt_{50}Rh_{50}/C and Pt_{100}/C electrocatalysts](image)

For each catalyst, the open-circuit voltages (OCV) were different, as would be 
expected in onset potentials. The OCVs of Pt_{50}Ru_{25}Rh_{25}/C, Pt_{50}Ru_{50}/C, Pt_{50}Rh_{50}/C, are higher 
than that of Pt_{100}/C, 0.54 V, and the order of OCV is exactly same as the onset potentials. The 
OCV of Pt_{50}Ru_{25}Rh_{25}/C is the highest value of 0.83 V, which is approximately 0.31 V higher 
than that of Pt_{100}/C. This indicates that Pt_{100}/C is more rapidly poisoned by CO than any other 
alloy catalyst and that the oxidation of adsorbed CO is enhanced by the second or third metal. 
In the case of Pt_{50}Ru_{25}Rh_{25}/C the overall performance is superior to that of the bimetallic 
electrocatalysts. The maximum power densities obtained for Pt_{50}Ru_{25}Rh_{25}/C, Pt_{50}Ru_{50}/C,
Pt_{50}Rh_{50}/C and Pt_{100}/C are 33.8, 29.6, 20.1 and 6.8 mW cm^{-2}, respectively (Table 5.4). We
conclude that the substitution of a small amount of Rh for Ru aids in cleaning surfaces poisoned by CO and provides additional reaction sites for methanol oxidation.

Table 5.4 Summary of performance of single fuel cell tests using (2 mg cm\(^{-2}\) catalyst loading, 40 wt% catalyst on carbon)

<table>
<thead>
<tr>
<th>Anode catalysts</th>
<th>Open circuit Voltage (V)</th>
<th>Maximum power density (mW cm(^{-2}))</th>
<th>Maximum current density (mA cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt(_{100})/C</td>
<td>0.54</td>
<td>6.8</td>
<td>49.4</td>
</tr>
<tr>
<td>Pt(<em>{50})Rh(</em>{50})/C</td>
<td>0.66</td>
<td>20.1</td>
<td>110.7</td>
</tr>
<tr>
<td>Pt(<em>{50})Ru(</em>{50})/C</td>
<td>0.71</td>
<td>29.6</td>
<td>149.3</td>
</tr>
<tr>
<td>Pt(<em>{50})Ru(</em>{25})Rh(_{25})/C</td>
<td>0.83</td>
<td>33.8</td>
<td>225.6</td>
</tr>
</tbody>
</table>

In membraneless fuel cells, pure Pt/C catalyst does not behave as a very good anode for methanol electro-oxidation due to its poisoning by strongly adsorbed intermediates such as CO (Vigier et al., 2004). The binary and ternary electrocatalysts performed better than Pt/C for methanol oxidation. Moreover, when the binary electrocatalysts were compared to the ternary ones in terms of oxidation the latter catalysts gave the best electrical performances. On the other hand, addition of Rh to Pt (Pt–Rh/C) had a little effect, whereas addition of Rh to Pt–Ru greatly enhanced the electrocatalytic activity.

As mentioned in our earlier studies that (Gowdhamamoorthi et al., 2014; Ponmani et al., 2014)), the performance of the developed membraneless fuel cell enhanced profoundly if the concentration of oxidant in cathodic stream is 10 times larger, and the current density is also increased approximately ten times.
5.4 Conclusions

In this work, the study of methanol oxidation on carbon-supported Pt–Ru–Rh ternary nanoparticles has revealed details concerning the activity and stability of the catalysts in membraneless fuel cells. The maximum activity for methanol oxidation was found for the Pt$_{50}$Ru$_{25}$Rh$_{25}$/C than the Pt$_{50}$Ru$_{50}$/C, Pt$_{50}$Rh$_{50}$/C and Pt$_{100}$/C. The significantly enhanced catalytic activity for methanol oxidation can be attributed to the high dispersion of ternary catalysts and to Rh acting as a promotion agent. XRD results show the homogenous alloy structure of Pt, Ru and Rh. The TEM images indicated an average size of Pt$_{50}$Ru$_{25}$Rh$_{25}$/C nanoparticles of 3-5 nm. The atom ratio of Pt, Ru and Rh from EDX analyses is close agreement with the original precursor concentration. The composition of ternary Pt$_{50}$Ru$_{25}$Rh$_{25}$/C nanoparticles can be conveniently controlled by adjusting the initial metal salt solution and preparation conditions. The electrochemical experiments showed that the Pt$_{50}$Ru$_{25}$Rh$_{25}$/C nanoparticles have higher catalytic activity than that of the other catalysts. We expect that the MLMFC may be a promising candidate for practical fuel cells to establish a clean and sustainable energy future. Further work is necessary to characterize the catalysts using different surface analysis techniques and to conduct tests of these electrocatalysts in microfluidic membraneless fuel cells.

References


