ETHANOL ELECTRO-OXIDATION ON PtCeO₂/C CATALYST IN DIRECT ETHANOL FUEL CELL

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Abstract. Anode catalyst of 20% PtCeO₂/C was prepared by colloidal method using ethylene glycol as the reductant. The prepared catalyst was characterized by X-ray diffraction (XRD) and transmission electron microscopy (TEM) techniques. TEM images show uniform dispersion of spherical metal nanoparticles with average diameter of 2.9±0.3 nm and close agreement with those estimated by Scherer formula from XRD results. Activity of the catalyst for ethanol electro-oxidation reaction (EOR) was tested in an electrochemical cell by cyclic voltammetry technique and in real fuel cell by in-situ differential electrochemical mass spectrometry (DEMS). The DEMS of fuel cell was also used to investigate the selectivity toward CO₂ formation by measuring the CO₂ current efficiency. Pt loading of anode catalyst (20% PtCeO₂/C) was about 0.8 mg/cm² and 2.5 mg/cm² for cathode catalyst (commercial 40% Pt/C). The results show that 20% PtCeO₂/C catalyst provided better performance in comparison to 20% Pt/C commercial catalyst.

Keywords: ethanol electro-oxidation reaction (EOR), CeO₂, CO₂ current efficiency, activity, selectivity

1.0 INTRODUCTION

Fuel cell has received an increasing attention because of its advantage compared to conventional energy conversion devices [1]. Among of the fuel cells types, proton exchange membrane fuel cell (PEMFC) is a low temperature fuel cell which has been rapidly developing. However, there are some problems in application of PEMFC due to gaseous fuel utilization i.e. hydrogen or hydrogen rich gas [6]. Using gaseous hydrogen fuel is more complicated due to bulky hydrogen storage and required external fuel reformer. Compared to PEMFC, direct alcohol fuel cell (DAFC) are more compact without the heavy and bulky external fuel reformer and can be applied especially to power electric vehicles. Liquid fuels, such as low-molecular weight alcohols (methanol and ethanol), have high energy densities and can be easily handled, stored and transported in comparison with gaseous fuels.

Currently, direct methanol fuel cell (DMFC) is being widely investigated as a possible power source for electric vehicles and other portable applications in the future. However, it is well-known that methanol is volatile and relatively toxic; therefore it is not
thought as a favorable and friendly fuel [1]. Other short chain organic chemicals, such as oxidation [1-5]. Among alternative fuels, ethanol is safer and has higher energy density compared to methanol (8.01 kWh kg\(^{-1}\) versus 6.09 kWh kg\(^{-1}\)). Moreover, ethanol can be easily produced by fermentation of sugar-containing raw materials. Therefore, ethanol is more attractive than methanol for direct alcohol oxidation fuel cells operating at lower temperature. The adsorption and oxidation of ethanol for fuel cells at lower temperature values have already been investigated, but most of the prior studies were restricted to the analysis of ethanol anodic oxidation mechanism and the identification of the reaction intermediates and products [7]. The complete ethanol electro-oxidation to CO\(_2\) involves releasing of 12 electrons per molecule and many adsorbed intermediates. Besides, ethanol is electrochemically oxidized through different pathways on different catalytic surfaces or in different media. Thus, it is more difficult to elucidate exactly the mechanism of ethanol electro-oxidation [2,5].

High activity and stability of Pt, especially under acidic environment, makes it a suitable electro-catalyst for electro-oxidation of many small chemical molecules. However, at room or moderate temperature values pure platinum is not a very good anode catalyst for ethanol or methanol electro-oxidation, because it is readily poisoned by the strongly adsorbed intermediates, including CO adsorption (CO\(_\text{ads}\)) which is always considered as one of the main poisoning species at low operating temperature.

CeO\(_2\) is well known as catalyst modifier in heterogeneous catalyst [13]. It was due to property of CeO\(_2\) as a good oxygen donor and oxygen container. The oxygen storage capacity associated with the ability to undergo a facile conversion between Ce(IV) and Ce(III) is one of its most interesting properties for electro-catalyst application to enhance in C-C bond breaking and convert intermediate product of CO to CO\(_2\).

Preliminary study of PtCeO\(_2\)/C catalyst for ethanol oxidation in alkaline medium was conducted by Shen et al. [12]. By testing in electrochemical cell, they found that Pt-CeO\(_2\)/C gave better performance than Pt/C catalyst.

In this work, PtCeO\(_2\)/C electro-catalyst with Pt:CeO\(_2\) weight ratio of 2:1, was prepared by alcohol reduction process [6]. Systematic study was carried out by testing the catalyst for ethanol oxidation using cyclic voltammetry in electrochemical cell and using in-situ differential electrochemical mass spectrometry (DEMS) of fuel cell. The aim of this research work is to investigate of PtCeO\(_2\)/C for ethanol electro-oxidation in direct ethanol fuel cell (DEFC) to improve capability for C-C bond breaking toward total oxidation reaction of ethanol.

### 2.0 Materials and Methods

#### 2.1 Material and Chemicals

The starting materials used in this experiment were: cerium nitrate hexahydrate (Ce(NO\(_3\))\(_3\).6H\(_2\)O, anal., Alfa-Johnson Matthew), hydrogen peroxide (30% H\(_2\)O\(_2\), p.a., Merck) and ammonium hydroxide (NH\(_4\)OH, 25 vol% p.a., Merck). H\(_2\)PtCl\(_6\)-6H\(_2\)O (Johnson Matthew) was used as precursors of PtCeO\(_2\)/C catalysts. Material of carbon support was Vulcan-XC-72 from Cabot Co.

In all experiments, 0.5 M sulfuric acid prepared from concentrated sulfuric acid (Merck suprapur), 0.1 sodium hydroxide (Merck suprapur) and water from a Milli-Q system (18 M\(\Omega\) cm) was used as electrolyte. One molar ethanol in 0.5M sulfuric acid solution was prepared,
using ethanol (LiChrosolv, 99 %) from Merck. High purity Ar (Linde Gas, 4.8) and CO (Linde Gas, N 4.7) were employed for electrolyte purging and CO saturation.

2.2 Preparation of CeO$_2$ and Carbon Supported PtCeO$_2$ Catalyst.

Synthesis of ceria was carried out by a two step precipitation method. The procedure in brief briefly described as follows; separate solutions of 0.1 mol Ce (III) nitrate in water and of 30 vol.% hydrogen peroxide were cooled to 5°C and then mixed together under constant stirring. After 8-10 min, the solution turned to first yellow then orange-yellow, but remained transparent. Ammonium hydroxide solution was then added to increase the pH value to 10. The solution was then refluxed at 90°C in oil bath for 2 hours. Precipitation therefore occurred in two stages. The solution was decanted and the precipitate was washed and dried at 80-85°C, then calcined at 500 °C in air for 3 h.

The needed amount of H$_2$PtCl$_6$·6H$_2$O was added into ethylene glycol solution and stirred for 30 min. Prior to the synthesis of colloidal solution, ethylene glycol was dried using molecular sieve. Then the pH value of the solution was adjusted to 12 with sodium hydroxide (0.5 M) and the solution was heated under reflux to 160 °C in an oil bath, and kept at this temperature for 2 h to obtain brown–black sol. The solution then cooled to room temperature and the calculated amount of as prepared CeO$_2$ and carbon Vulcan XC-72 was added to the sol and stirred for another 12 h. The obtained black product was then filtered and extensively washed with distilled water, and dried at 80°C for overnight.

2.3 Physical Characterization

X-Ray diffraction was performed using instrumentation of Bruker D8 Advanced diffractometer equipped with a Cu anticathode, adjustable divergence slit, graphite monochromator on the diffracted beam and proportional detector. Data acquired at 2θ range from 20 to 65°, scan step of 0.02° and fixed counting time of 6 s for each step.

Transmission electron microscopy (TEM) investigations were carried out using the JEOL JEM 2000 EX microscope operating at 120 kV. High Resolution Transmission Electron Microscopy (HRTEM) images were taken on JEOL JEM 2010 F operating at 200 kV.

2.4 Electrochemical Characterization in Half Cell Setup

10 mg catalyst sample was suspended in 0.3 mL distilled water and 0.5 mL of 10.0 wt.% Nafion in alcohol was added as binder and proton conductor. The mixture was ultrasonically processed for 10 min to form homogeneous ink. Then 13.5 micro liter of ink were pipetted on a vitreous electrode with 6 mm diameter to act as the working electrode.

An electrolyte solution was prepared by adding ethanol to a sulfuric acid solution to obtain concentration of 1 mol dm$^{-3}$ ethanol + 0.5 mol dm$^{-3}$ H$_2$SO$_4$. After deaerating the solution with Argon gas, electrochemical measurements were conducted on this solution using potential control methods (Potentiostat, Autolab PGstat 20) which involve the electrode of the comparative samples as a working electrode and a platinum wire as a counter electrode, while Hg/Hg$_2$SO$_4$ (0.5 M) was used as a reference electrode.
2.5 Preparation of Membrane Electrode Assembly (MEA)

In-house PtCeO$_2$/C catalyst was used for preparation of anode. 40% Pt/C commercial catalyst (ETEK) was used as cathode catalyst. In order to make MEA, a suspension of catalyst powder, Nafion® solution (from Du Pont) and isopropanol were treated in an ultrasonicator. The ink was sprayed onto porous carbon backing layer (Toray paper from ETEK, TGP H 060, no wet proofing) held at 110°C. The 1.2 cm$^2$ patches of the Toray paper comprising sprayed catalyst layers were then cut and hot pressed with the Nafion® 117 membrane in between at 140°C for 5 min at a pressure of 1 kN.cm$^{-2}$. In order to keep the thickness of the anode electrocatalyst layer constant, we kept the amount of catalyst powder (Pt loading) around 0.8 mg cm$^{-2}$ for anode catalyst and of around 2.5 mg cm$^{-2}$ for cathode catalyst.

2.6 In-situ Differential Electrochemical Mass Spectrometry (DEMS) of Fuel Cell

The DEMS setup that consisted of two differentially pumped chambers, a Balzers QMS 200 mass spectrometer, AGGF potentiostat and computerized data acquisition system. The DEMS sensor was located at the outlet channel of anode compartment, it consist of a cylindrical detection volume with a diameter of 7 mm and a height of 2 mm through which anode outlet flow passes. This volume was separated from the vacuum system of the mass spectrometer by a Microporous Teflon membrane (Schleicher & Schuell, TE30) with a pore size of 0.02 micrometer and a thickness of 110 micrometer. The membrane is supported by a Teflon disc of 2 mm in diameter, with holes.

The fuel cell consists of two stainless steel plates with integrated serpentine medium distribution channels. This DEMS measurement was carried out in the fuel cell setup with cell dimension 1.2 cm$^2$.

Cathode with Pt loading (2.5mg/cm$^2$) and continuous hydrogen flow works as counter and reference both. Potential of the cathode is assumed to be same as of the reversible hydrogen electrode (RHE). All potential are reported in reference to this.

The anode flow system comprised of a tank filled with ethanol solution and a tank filled with water. These tanks were connected via heated tubes with the three-way valve at the fuel cell inlet. The ethanol solution and the Millipore water were deaerated with argon gas for 40 min. A dosing pump between the cell outlet and exit tank controls the flow of ethanol solution and water through the cell. To avoid the gas bubble formation due to the large gas production and low solubility of CO$_2$ at elevated temperature, the anode flow system was pressurized at 3 bars overpressure. The cathode overpressure was kept at 1 bar to limit the crossover of H$_2$ to anode side. Schematic diagram of DEMS setup is shown in Figure 1.
3.0 RESULTS AND DISCUSSION

The XRD patterns of Pt/C and Pt-CeO$_2$/C are shown in Figure 2. From the Figure 2 (a), the characteristic peaks located at $2\theta$: 28.5°, 33.1°, 47.5°, 56.3° and 59.01° are corresponding to \{111\}, \{200\}, \{220\}, \{311\} and \{222\} planes, respectively. These match well with the peaks of cubic fluorite CeO$_2$ crystal structure in XRD-pattern database.
Figure 2 XRD pattern of (a) CeO$_2$ (solid line) (b) Pt/C (JM) (dashed line) and (c) Pt-CeO$_2$/C (dot line)

Figure 2 (b), represents the XRD pattern of commercial catalyst Pt/C (JM). The first peak at $2\theta \approx 23^\circ$ originates from the Vulcan XC-72 carbon support. The peaks at $2\theta \approx 40.04^\circ$ are reflections of the face centered cubic (f.c.c.) crystal lattice of Pt $\{111\}$. The peaks indicated with a star (*) was due to the sample holder. Figure 2 (c) presents the XRD pattern of PtCeO$_2$/C catalyst. All of the peaks which are corresponding to CeO$_2$, platinum and carbon were exist in the XRD pattern result. This clearly indicates that the PtCeO$_2$/C catalyst was successfully prepared by ethylene glycol reduction method.
Both XRD and TEM results indicate that all catalysts investigated in present work have similar nano particle sizes and the method is suitable to prepare nanometer catalysts with higher metal loading. From the TEM micrographs, it was found that metal particles of PtCeO$_2$/C catalyst are uniform. The mean particles size obtained by TEM analysis is 2.9±0.3 nm. The mean particles size value is in good agreement with those calculated from the XRD results using Scherer formula of about 3.1 nm.

### 3.1 Activity Test in Electrochemical Cell

Figure 4 shows the results of CV test of commercial carbon supported platinum and the carbon supported Pt-CeO$_2$ catalyst prepared in this study. From the Fig.4 (a) can be seen that there is no differences between CV of Pt/C and PtCeO$_2$/C, because of CeO$_2$ itself hasn’t any feature of CV. However, in presence of ethanol Fig. 4 (b), it is clear that addition of the CeO$_2$ to Pt results in the negative shift of the on set potential oxidation of ethanol. The on set potential oxidation of ethanol on PtCeO$_2$/C catalyst at about 0.40 V (vs. reference hydrogen electrode (RHE)) and on Pt/C at about 0.5 V (vs. RHE). It means that PtCeO$_2$/C catalyst was more active for ethanol oxidation than Pt/C catalyst. This result agreed to the results from Shen et al. which studied in the alkaline medium [12]. However, it is important to gain more understanding of the ethanol electro-oxidation reaction (EOR) especially to study the selectivity to CO$_2$ product. EOR mechanism in alkaline medium is difficult to investigate because the main product CO$_2$ is highly soluble in aqueous alkaline electrolytes, due to the formation of carbonates and bicarbonates which renders it difficult to observe with technique such as differential electrochemical mass spectrometry (DEMS).

The current density in Figure 4 (b) is the current which is obtained and normalized by electrochemical active surface area (EAS). This EAS was determined from CO stripping voltammetry [9]. EAS value which is obtained in these experiments for Pt/C and PtCeO$_2$/C catalysts are 23.6 and 23.8 cm$^2$, respectively.
At almost the same of EAS for CO adsorption, PtCeO$_2$/C catalyst was more active than Pt/C catalyst for electro-oxidation of ethanol.

![Figure 4](image)

**Figure 4** Cyclic voltammogram of 20% Pt/C (solid line) and 20% PtCeO$_2$/C (dashed line) at 30°C, scan-rate 10 mV s$^{-1}$, in 0.5M H$_2$SO$_4$ solution (a) in 0.5M H$_2$SO$_4$ solution + 1.0M ethanol.

From the linear slopes of the integrated charges in the Arrhenius plots in Figure 5 we determined the averaged apparent activation energies ($E_{app}$) for the overall ethanol electro-oxidation reaction. From the Faradaic current plot in Fig.5, we determined $E_{app}$ was about 29 kJ/mol for ethanol oxidation over a PtCeO$_2$/C catalyst and of about 30.5 kJ/mol over Pt/C catalyst at temperature range of 30-60 °C. This means that electro-oxidation of ethanol over PtCeO$_2$/C catalyst is slightly active than over Pt/C reference catalyst. However, these values were higher when compared to the $E_{app}$ of methanol which was reported as 21 kJ/mol [10]. The rather high value of $E_{app}$ over PtCeO$_2$/C and Pt/C catalyst for ethanol electro-oxidation, is because the (complete) oxidation of ethanol to CO$_2$ includes a C-C bond cleavage, which is mostly requires higher activation energies. From the values of $E_{app}$ for ethanol electro-oxidation over PtCeO$_2$/C and Pt/C indicated that the ethanol oxidation favor occurred on PtCeO$_2$/C than Pt/C catalyst.
3.2 Activity and Selectivity Test by In-Situ Differential Electrochemical Mass Spectrometry of Fuel Cell

The product distribution of the ethanol oxidation over 20% Pt/C reference catalyst and as prepared 20% PtCeO$_2$/C catalyst was performed. It is known that the different oxidation products of ethanol are carbon dioxide, acetaldehyde and acetic acid [4]. However, only the first two products were detected by using DEMS technique, due to low volatility of acetic acid.

Ethanol electro-oxidation products on Pt/C catalyst at temperature 90 °C in 0.1 M ethanol and 0.5 M H$_2$SO$_4$ was shown in Fig.6. This includes the Faradaic current cyclic voltammogram (CV) (a) and the corresponding mass spectrometric cyclic voltammogram (MSCV) for the ion currents $m/z = 29$ (b), $m/z = 30$ (c), $m/z = 22$ (d), and $m/z = 15$ (e). The steady-state cyclic voltammogram for ethanol electro-oxidation on the Pt/C (Vulcan-XC72) catalyst was recorded after several cycles as shown in Figure 6.

The electro-oxidation of ethanol on Pt/C at potential below 0.4 vs RHE could be largely blocked by intermediate product like CO and hydrocarbon residue. Xia et al. found the CO is one of an intermediate product in ethanol electro-oxidation over Pt/C catalyst by fourier transform infrared spectroscopy (FTIR) technique [5]. The CO was adsorbed strongly onto Pt surface at low potential caused surface poisoning of Pt. These adsorbed species can be removed by oxidative scanning at potential of about 0.5 V vs RHE.

Therefore, the onset of ethanol oxidation in the positive going scan of the steady-state voltammogram occurs at ca. 0.5 V (Figure 6.a)
Figure 6 cyclic voltammogram (CV) and mass spectrometric cyclic voltammogram (MSCV) of 20% Pt/C catalyst at temperature 90°C, ethanol flowrate 5 ml/min, scanrate 5 mV/s (a) CV (b) MSCV for m/z = 29 (c) MSCV for m/z = 30 (d) MSCV for m/z = 22 and (e) MSCV for m/z = 15
Figure 7 CV and MSCV of 20% Pt-CeO$_2$/C catalyst at temperature 90°C, ethanol flowrate 5 ml/min, with scan rate 5 mV/s (a) CV (b) MSCV for m/z = 29 (c) MSCV for m/z = 30 (d) MSCV for m/z = 22 and (e) MSCV for m/z = 15

Electro-oxidation of ethanol on PtCeO$_2$/C catalyst under the same conditions to the Pt/C reference catalyst was presented in Figure 7. CV of Faradaic current in Figure 7(a) indicated that the on-set of ethanol oxidation reaction on PtCeO$_2$/C was shifted to the negative potential in comparison to the Pt/C catalyst (Fig.6(a)). The on-set potential of ethanol over PtCeO$_2$/C occurred at potential of about 0.4 V vs. RHE. Mass spectrometric cyclic voltammogram (MSCV) for the ion currents m/z =29 (b), m/z = 30 (c), m/z = 22 (d), and m/z = 15 (e) show the results which was similar trend for both of catalysts.

The PtCeO$_2$/C catalyst was more active for ethanol electro-oxidation reaction in fuel cell setup than commercial Pt/C catalyst. These results agreed with the previous results in electrochemical half cell test. This reaction resulted products like: CO$_2$, acetaldehyde, methane and ethane which was can be detected by in-situ DEMS technique. While, acetic
acid which was reported could be detected by FTIR [4], cannot be detected by this DEMS measurement.

### 3.3 CO₂ Current Efficiency

Fig. 8 shows the Faradaic current vs potential for different catalysts. Testing performance in DEMS is conducted at temperature 90 °C, 5 ml/min ethanol flowrate, and with scanrate of 5 mV/s by potentiostatic measurements. This result indicates that Faradaic current of catalysts with added ceria provides higher current at low potential (up to 0.6 V) in comparison to commercial Pt/C catalyst reference. At potential > 0.6 V, the Faradaic current resulted from Pt/C catalyst is higher than the PtCeO₂/C catalyst. This means that by adding ceria on Pt-based catalyst, activity could be increased of the catalysts at low potential, although this elevation in Faradaic current was not so high. Increase of Faradaic current over PtCeO₂/C catalyst compared to Pt/C catalyst at potential up to 0.6V vs RHE was 5 - 15 %. Meanwhile, at potential > 0.6 V vs RHE, increase of Faradaic current over Pt/C catalyst compared to PtCeO₂/C was 20-40%. This increase of the Faradaic current at low potential was more useful in fuel cell application, because magnitude of the overall cell potential is still significant. Therefore we want to further investigate increase of Faradaic current at the low potential by analyzing ion mass current at m/z = 22 as shown in Figure 9.

![Figure 8](image)

**Figure 8** Faradaic current vs. potential of fuel cell setup at temperature 90°C, scanrate 5 mV/s, anode catalyst loading 0.8 mg/cm² for 20% PtCeO₂/C (dashed line) and 20% Pt/C (solid line), cathode catalyst loading 2.5 mg/cm² (40% Pt/C)

Figure 9 shows relation between CO₂ current efficiency (CCE) versus potential. It is shown that the CO₂ current efficiency is a strongly dependent on the potential. Furthermore an increase in Faradaic current which is observed at low potential (Figure 8) was followed by significantly increasing of CO₂ current efficiency. Hence, commercial Pt/C reference
catalyst provided lower performance for ethanol oxidation reaction than PtCeO\textsubscript{2} catalyst, especially at low potential (≤ 0.6 V).

The CO\textsubscript{2} current efficiency maximum was obtained at potential 0.6 V vs RHE. At this potential, increasing CCE over PtCeO\textsubscript{2}/C was about 18 % in comparison to reference catalyst. This trend can be explained by the fact that electro-oxidation of ethanol at potential below ca. 0.4 V is largely blocked by adsorbed poisoning intermediates (CO and hydrocarbon residues). The decrease in CO\textsubscript{2} current efficiency after 0.6 V is a bit surprising result, since the peaks of Faradaic current and ion current m/z= 22 were occurred at potential of about 0.7 V vs RHE (Figure 7). Although we can expect that at potentials > 0.8 V the Pt surface is mostly covered by PtO, which may hinder the complete oxidation of ethanol, but will support formation of oxidation by-product like acetaldehyde or acetic acid which was detected using FTIR technique by Xia et al.[5].

![Graph](image)

**Figure 9** CO\textsubscript{2} current efficiency vs. potential, at temperature 90°C, scanrate 5 mV/s, anode catalyst loading 0.8 mg/cm\textsuperscript{2} for 20% PtCeO\textsubscript{2}/C (dashed line) and 20% Pt/C (solid line), cathode catalyst loading 2.5 mg/cm\textsuperscript{2} (40% Pt/C).

It is clearly that modified Pt catalyst by CeO\textsubscript{2} increasing performance of catalyst for ethanol electro-oxidation reaction. Increasing of CO\textsubscript{2} current efficiency as an indication that ethanol oxidation reaction was taken place through total oxidation reaction. Improvement of the CO\textsubscript{2} current efficiency also as an indication that the C-C bonds breaking was occurred in the ethanol oxidation reaction. It was because mostly CO\textsubscript{2} product was resulted from oxidation of CO\textsubscript{ads} species of ethanol as an intermediate product of C-C bond breaking. The role of CeO\textsubscript{2} in the oxidation of carbon monoxide was agreed to what reported by Thi et al. [14]:

\[
CO + 2CeO_2 \rightarrow CO_2 + Ce_2O_3
\]
The mechanism could be explained that oxygen was extracted from an exposed surfaces of the CeO$_2$ that promote oxidation of CO$_{ads}$ on Pt surface to CO$_2$ product, facilitated by reduction of Ce$^{4+}$ to Ce$^{3+}$ at low potential ≤ 0.6 V vs RHE.

4.0 CONCLUSION

20% PtCeO$_2$/C catalyst which is prepared by colloidal methods was an active catalyst for ethanol electro-oxidation reaction compared to the commercial Pt/C catalyst. Increasing performance in activity for EOR was indicated by increment of Faradaic current either in half cell electrochemical test or in DEMS of fuel cell test. Moreover, the increasing in selectivity to the CO$_2$ formation was indicated by increment of the CO$_2$ current efficiency in DEMS of fuel cell test. Both increasing of the activity and selectivity were occurred at low potential less than 0.6 V vs. RHE.

Increase of Faradaic current over PtCeO$_2$/C catalyst compared to Pt/C catalyst at potential 0.6V vs RHE was about 6%. Increasing of selectivity toward CO$_2$ formation on PtCeO$_2$/C catalyst was about 18% at potential 0.6 V vs RHE in comparison to Pt/C catalyst.

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