Electrolysis of Carbon Dioxide in a Solid Oxide Electrolyzer with Silver-Gadolinium-Doped Ceria Cathode

Yongmin Xie,a,b Jie Xiao,b Dandan Liu,b Jiang Liu,a,b,c,d and Chenghao Yanga

aNew Energy Research Institute, School of Environment and Energy, South China University of Technology, Guangzhou 510006, People’s Republic of China
bThe Key Laboratory of Fuel Cell Technology of Guangdong Province, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510641, People’s Republic of China

Energy storage plays an extremely important role in peak load shifting of traditional power plants and in effective application of intermittent renewable energies such as solar, wind, and tide, etc.1-3 Solid oxide electrolyzers (SOEs) have attracted more and more attention in recent years due to their environmental-friendliness and high efficiency in storing energy by converting electrical energy into chemicals such as hydrogen or carbon monoxide through electrolysis of water or carbon dioxide.4,5 In principle, SOEs work in the reverse manner of high temperature solid oxide fuel cells (SOFCs).6 A cathode of an electrochemical cell is the electrode where reduction reaction occurs, and an anode is where oxidation reaction occurs. An electrode functioning as the anode of an SOFC will work as the cathode when the cell is operated in an SOE mode. At the same time, the cathode of the SOFC is shifted to be the anode of the SOE. Nevertheless, the electrode on the air or oxygen side always has a higher potential than that on the fuel (or CO2 rich or H2O rich) side. The former electrode can be called as oxygen electrode or positive electrode (+) and the latter fuel electrode or negative electrode (−), as marked in Fig. 1. Using external electricity, SOEs are able to electrochemically convert steam to hydrogen and carbon dioxide to carbon monoxide at the fuel electrode. At the same time, pure oxygen can be obtained at the oxygen electrode.

While high temperature steam electrolysis has got great progress in producing hydrogen, which is a well-known green alternative fuel electrode.7 Although Pt electrode. Recently, there have been some works on Ni-cermet fuel electrode.16-18 O. Costa-Nunes et al.28 reported that the maximum power density of an SOFC with Ni-YSZ electrode operating on pure CO was only 50% of that using pure H2 as fuel. In addition, Ni in a pure CO2 atmosphere at high temperature tends to be oxidized into NiO, resulting in electrical and mechanical problems, which may be solved by feeding CO/CO2 with some CO.16,17 However, carbon deposition may be formed on Ni to deactivate the electrode with high CO concentration in the cell because Ni catalyzes the Boudouard reaction (2CO = CO2+C).17 To date, there have been some reports confirming the feasibility and superiority of direct electrolyzing CO2 without feeding reducing gas.26-28 Gorte et al.29 found that SOE with Lao.8Sr0.2O1.9 (LST) composite fuel electrode can operate in pure CO2. However, the large reducing potential required for CO2 reduction can cause structural change of LSCM, leading to a large polarization resistance. Xie et al.30 have reported that SOE with La0.8Sr0.2TiO3-δ (LST) composite fuel electrode without pre-reduction can be used for electrolysis of H2O and CO2. They found that the Faraday efficiency of the CO2 reduction was much lower than that of H2O and they attribute this fact to the passivation of CO2 on the LST electrode.

Recently, our group and some other researchers found that SOFCs with porous Ag-GDC (Ce0.9Gd0.1O1.9, gadolinium-doped ceria) cermet as the fuel electrode materials show promising performance and good stability in CO or CO2 mixture.31,32 Ag possesses high electric conductivity and chemical stability in oxidizing atmospheres above 200°C. GDC has high ionic conductivity and good catalytic properties toward CO2 reduction in reducing CO/CO2 atmospheres.15 Hence Ag-GDC may be a promising fuel electrode material for pure CO2 electrolysis in SOEs at large reducing potentials. In this work, porous Ag-GDC electrode is investigated for CO2 electrolysis in tubular YSZ electrolyte-supported SOE without reducing gas feeding. The electrochemical performance of the SOE with Ag-GDC fuel electrode in CO2 electrolysis has been examined and discussed in detail.

Experimental

Fabrication of the electrolyte tubes.— Tubular YSZ electrolyte was fabricated by dip coating technique.34 25 g YSZ powder
Characterization.—The as-prepared cells were attached to one end of a ceramic tube by using silver paste as sealing and jointing material. Silver wires (0.25 mm in diameter) were attached on the electrodes as leading wires. A four-probe set-up was adopted to eliminate ohmic loss in the electrical circuit. The single cells were initially tested in SOFC mode, with humidified hydrogen (3 vol.% at 25°C, 50 mL min⁻¹) as fuel and ambient air as oxidant, at 800°C. Then the tested cells were cooled down to room temperature and prepared for CO₂ electrolysis testing. Fig. 1 shows the schematic diagram of the electrolyzer CO₂ electrolysis testing set. The LSM-based air electrode was exposed to the ambient air, whereas the fuel electrode compartment was supplied with pure CO₂ at a flow rate of 30 mL min⁻¹. The electrochemical measurements were conducted using an Iviumstat Electrochemical Analyzer (Ivium Technologies B.V., Netherlands). The electrochemical impedance spectra of the electrolyzer was recorded under open circuit as well as under different applied voltages with an amplitude of 10 mV, in the frequency range 0.1 Hz-100 kHz. The electrolyzer was also tested under constant current densities of 0.25, 0.50 and 0.75 A cm⁻² for a short-term, respectively. The output gas from the cathode was supplied to an on-line gas chromatography (GC9800, Science Technology INC, Shanghai), equipped with a thermal conductivity detector (TCD). The column of the gas chromatography is TDX-01 (1 m × 3 mm). After completion of the constant voltage electrolysis experiments, the open circuit voltage (OCV) of the electrolyzer was recorded to examine the status of the electrolyzer. Then a stability test of the CO₂ electrolysis was performed with an electrolyzer at a constantly applied voltage of 1.59 V. The microstructure of the electrolyzer after electrochemical testing was characterized using a scanning electron microscope (Philips XL-30FEG, Holland).

Results and Discussion

Microstructure of the cell.—Figure 2 shows the microstructure of the cell section and the surface of the Ag-GDC electrode. Fig. 2a is the cross section microstructure of the as-prepared Ag-GDC fuel electrode/YSZ electrolyte bilayer, showing an approximately 20 μm-thick porous Ag-GDC electrode well adhered to the relatively dense YSZ electrolyte. Fig. 2b is a surface view of the Ag-GDC fuel electrode after operating in both SOFC and SOE modes at 800°C. It can be seen that the Ag has some agglomeration after about 20h-operation test, which may be avoided by optimizing the proportion of Ag and GDC.

Performance of the cell as an SOFC.—Fig. 3 shows the performance of the cell operated at 800°C, in SOFC mode, using humidified hydrogen (3 vol.% H₂O at 25°C) as fuel and ambient air as oxidant. As can be seen, the OCV (open circuit voltage) is approximately 1.07 V, which is comparable to the theoretical prediction (1.1 V). The OCV of an SOFC can represent the gastight of the electrolyte containing the cathode, anode, and electrolyte. It is calculated that the hydrogen gas-leak-rate of the electrolyte, corresponding to the SOFC, is approximately 1.07 V, is 1.29 × 10⁻²² mol m⁻² s⁻¹, over 10 orders lower than the hydrogen consumption rate of a SOFC operated at a current density of 1 A cm⁻² (5.18 × 10⁻²² mol m⁻² s⁻¹). The maximum power density of the SOFC is 277 mW cm⁻².

Performance of the cell as an SOE for CO₂ electrolysis.—When pure CO₂ is introduced into the fuel electrode and ambient air is surrounded the oxygen electrode of a solid oxide cell, a voltage will be established between the two electrodes because of different oxygen partial pressure on the two sides. The cell at this state is an oxygen concentration cell and the established voltage is the theoretical OCV. According to Nernst equation, the OCV can be presented as Eq. 1:

$$V_{OCV} = \frac{RT}{4F} \ln \frac{p_{O_2,\text{oxygen}}}{p_{O_2,\text{fuel}}}$$  \[1\]

Where \(p_{O_2,\text{oxygen}}\) and \(p_{O_2,\text{fuel}}\) are the oxygen partial pressures on the air and fuel electrodes, respectively, \(R\) is the gas constant, \(T\) is the temperature, \(F\) the Faraday constant. In pure CO₂, the oxygen partial pressure is determined by chemical equilibrium, which is
calculated as 4.57 \times 10^{-7} \text{ atm}. Thus, taking the oxygen partial pressure in air as 0.21 \text{ atm}, the OCV at 800 \degree \text{ C} is calculated as 0.3 \text{ V}.

Fig. 4 shows the I-V curve of the electrolyzer for CO2 electrolysis from 0 to 2 V at 800 \degree \text{ C}. As can be seen, the experimental OCV of the electrolyzer is approximately 0.09 \text{ V}, much smaller than 0.3 \text{ V}, indicating the oxygen partial pressure in the applied CO2 is much higher than that predicted from pure CO2. The actual oxygen partial pressure in the CO2 calculated according to Eq. 1 is 4.3 \times 10^{-3} \text{ atm}. There has been previous observation on the similar evidence and our GC measurement of the initial CO2 also roughly confirmed there is about 0.23% of O2 impurity, which corresponds to an oxygen partial pressure of 2.3 \times 10^{-3} \text{ atm}, in the same order with the value calculated from Eq. 1. When the applied electrical voltage is lower than the OCV (0.09 \text{ V}), O2 is converted to O2^- at the air electrode and then the O2^- transports through the electrolyte to the fuel electrode, resulting in a positive current (an external current flow from the positive electrode to the negative electrode). The electrolyzer is working as an oxygen concentration cell. When the applied voltage is in the range of 0.09-0.22 V, the electrolyzer is working as an oxygen pumper that oxygen in the CO2 atmosphere is transported through the electrolyte to the air side along with a negative current through the external circuit. The electrolyzer operated as either concentration cell or oxygen pumper involves oxygen transportation and no other chemical reactions occur. The I-V curve below 0.22 V is almost linear, suggesting that the activity of the Ag-GDC electrode toward O2 reduction is similar to that of LSM-YSZ. When the applied voltage exceeds 0.22 V, the current density of the electrolyzer no longer increases with voltage because O2 at the fuel electrode side becomes exhausted. As shown in Fig. 4, the unchanged current density corresponds to the voltage range of 0.22 V to 0.7 V is 20 mA cm^{-2}, which is equivalent to a current of 40 mA because the effective area of the cell is 2 cm^2. It can be calculated that, with this current, the oxygen is pumped from the CO2 side to the air side at a rate of 0.139 mL min^{-1}, from which the oxygen partial pressure of 4.6 \times 10^{-3} \text{ atm} in the CO2, which fits very well with the value calculated from Eq. 1 (4.6 \times 10^{-3} \text{ atm}), can be deduced, considering the flow rate of CO2 is 30 mL min^{-1}.

When pure CO2 is introduced to an SOE for reduction, the theoretical minimum electrolytic voltage (decomposition voltage) is the OCV calculated from Eq. 1, i.e., 0.3 \text{ V} at 800 \degree \text{ C}. This is a significant advantage of electrochemical reduction of CO2 in an SOE operates with pure CO2, in contrast to that with reducing gas feeding, which requires high electrolytic voltage (e.g. theoretical minimum electrolytic voltage of 0.94 \text{ V} for 50\% CO2–50\% CO at 800 \degree \text{ C}). Fig. 4 shows that the measured decomposition voltage for CO2 reduction in the SOE is approximately 0.7 \text{ V}, reflecting the overpotential of 0.4 \text{ V}. Contrary to the situation of an SOFC, any electronic leak through the electrolyte of an SOE will give an artificially better performance. The measured OCV of the cell operated in an SOFC mode, with humidified hydrogen as the fuel, is 1.07 \text{ V} 0.03 \text{ V} lower than the theoretical OCV. This corresponds to about 3\% electronic leak. The apparent electronic leak
should be caused by gas leaking through the electrolyte or sealant, because the electrolyte material YSZ is a pure ionic conductor and its electronic conductivity can be neglected. The gas leaking rate of H₂ is much smaller than that of CO or CO₂. Therefore the electronic leak of the SOEs of the present work is less than 3%. The detailed value is analyzed later.

The performance shown in Fig. 4 is better than those reported CO₂ electrolyzers with YSZ-based electrode. This may be due to the reduction of GDC (Ce⁴⁺→Ce³⁺) under electrical loadings, similar to the reported LSCM-GDC which showed higher performance than LSCM-YSZ toward CO₂ reduction under 1.0 V above OCV. The electrochemical reaction in the fuel electrode could be described as following, using Kröger–Vink notation:

\[
\text{CO}_2(g) + V_{o}^{\bullet} + 2e^- = \text{CO}(g) + O_{o}^{\bullet}
\]  

Where e⁻ represents free electron from the electrode, \(V_{o}^{\bullet}\) and \(O_{o}^{\bullet}\) denote oxygen vacancy and oxygen ion in the GDC lattice, respectively.

The reduction of GDC improves mixed conductivities of the electrode, note oxygen vacancy and oxygen ion in the GDC lattice, respectively. The reduction of GDC improves mixed conductivities of the electrode, therefore favors the reaction (2). The current density approaches 1359 mA cm⁻² with an applied voltage of 2 V at 800°C. The encouraging performance results implying that the Ag-cermet electrodes are feasible for reduction of pure CO₂.

Fig. 5 shows typical impedance spectra of the SOE at operating voltages of OCV (0.09 V), 0.69 and 0.99 V, respectively. For each spectrum curve, the first intercept of the real axis at high frequency corresponds to ohmic resistance (\(R_s\)). The real axis range covered by the arc at lower frequency region is considered to be electrode polarization resistance (\(R_p\)). As can be seen, the \(R_s\) decreases slightly with applied voltage, while the \(R_p\) changes significantly regarding to the applied voltage. The polarization and ohmic resistances corresponding to the operating voltages are shown in Fig. 6. Obviously, the polarization resistance corresponding to the voltage within the large overpotential range (̃0.25-0.75 V) is significantly larger than those out of the range. At high voltage out of the large overpotential range, the main electrochemical process is CO₂ reduction and \(R_p\) decreases slightly with increasing voltage. The change of electrochemical impedance spectra of the SOE under different applied voltages is well consistent with the trend of the \(I-V\) curve as shown in Fig. 4. When the voltage is higher than 1 V, \(R_p\) becomes lower than \(R_s\), suggesting that ohmic resistance dominates the loss at high cell voltages.

Fig. 7 shows short-term performances of the SOE for CO₂ electrolysis maintained at current densities of 0.25, 0.50 and 0.75 A cm⁻² (0.5, 1.0, and 1.5 A), respectively, at 800°C. As can be seen, the performance results are stable, with voltages of approximately 1.14, 1.41 and 1.65 V, corresponding to the operating current densities, respectively.

The theoretical outlet volumetric flow rate of CO produced from the SOE is related to current supplied during the electrochemical reaction and could be described through the Faraday’s law as Eq. 3:

\[
N_{CO} = \frac{60(j - j_0)SV_{stad}}{nF} \times 10^3 \tag{3}
\]

Where \(N_{CO}\) (mL min⁻¹) is the outlet CO volumetric flow rate, \(j\) (A cm⁻²) the applied current density, \(j_0\) (A cm⁻²) the current density for removing molecular oxygen in CO₂, \(S\) (cm²) the effective area of the SOE, \(V_{stad}\) (L mol⁻¹) the volume of 1 mol gas at standard temperature and pressure, \(n\) the number of the electrons involved in the reaction, \(F\) (C mol⁻¹) the Faraday constant. Meanwhile, the practical outlet CO volumetric flow rate (\(N_{CO}'\)) can be obtained by an on-line gas chromatography and the Farady efficiency of the CO₂ electrolysis is

\[
\eta_{farad} = \frac{N_{CO}'}{N_{CO}} \times 100\% \tag{4}
\]

According to Eq. 3 and 4, the CO producing rates of the SOE operated at currents (\(j_S\)) of 0.5, 1.0 and 1.5 A are approximately 3.2,
During CO2 electrolysis in SOEs, energy is consumed to obtain CO because the enthalpy, which is considered as the chemical energy, and Gibbs free energy, which can be converted to electrical energy, of CO are much higher than those of CO2. Taking the electrical energy supplied to the SOE system as the consumed energy and the Gibbs free energy of the produced CO as the effectively converted energy, the electrical energy conversion efficiency can be written as

\[
\eta_{\text{elec}} = \frac{N_{\text{CO}}' \Delta H_m^0(CO)}{60 V_{\text{rad}} j S V}
\]

Where \(\Delta H_m^0(CO)\) is the enthalpy of CO2 reduction, which is 283.32 kJ mol\(^{-1}\) at 800°C.

Note that when a CO molecule is formed, not only the Gibbs free energy is increased but also the enthalpy. If the increased enthalpy is taken as the effectively converted energy, then the energy conversion efficiency of CO2 electrolysis can be described as

\[
\eta_{\text{energ}} = \frac{N_{\text{CO}}' \Delta H_m^0(CO)}{60 V_{\text{rad}} j S V}
\]

Where \(\Delta H_m^0(CO)\) is the enthalpy of CO2 reduction, which is 283.32 kJ mol\(^{-1}\) at 800°C.

As shown in Table I, while the Faraday efficiency and productivity are increasing with the applied current, the electrical energy conversion efficiency and the chemical energy conversion efficiency are decreasing with the current. Note that the chemical energy conversion efficiency at the smallest current, 0.5 A, is 114% which exceeds 100%. This is because only the supplied electrical energy is taken as the consumed energy and the heat energy is not considered. In fact, the chemical energy of CO cannot only come from the supplied electrical energy but also the heat supplied to maintain the operating temperature. This is also the especial advantage of high temperature electrolysis that it can effectively use the waste heat of fire or nuclear power plant, etc..

Table I. Parameters of the SOE with Ag-GDC cathode, operated at currents of 0.5, 1.0 and 1.5 A, respectively, at 800°C. (\(N_{\text{CO}}\)): measured CO production; \(N_{\text{CO}}'\): calculated CO production; \(\eta_{\text{Fara}}\): Faraday efficiency; \(\eta_{\text{prod}}\): CO productivity; \(\eta_{\text{elec}}\): electrical energy conversion efficiency; \(\eta_{\text{energ}}\): chemical energy conversion efficiency.

| j (A) | \(N_{\text{CO}}\) (mL min\(^{-1}\)) | \(N_{\text{CO}}'\) (mL min\(^{-1}\)) | \(\eta_{\text{Fara}}\) (%) | \(\eta_{\text{prod}}\) (%) | \(\eta_{\text{elec}}\) (%) | \(\eta_{\text{energ}}\) (%) |
|------|-------------------------------|-------------------------------|----------------|----------------|----------------|----------------|
| 0.5  | 3.2                           | 3.1                           | 96.9           | 10.3           | 75.4           | 114.0          |
| 1.0  | 6.7                           | 6.6                           | 98.5           | 22.0           | 65.2           | 98.6           |
| 1.5  | 10.2                          | 10.0                          | 98.5           | 33.3           | 56.5           | 84.7           |

6.7, and 10.2, respectively. The measured outlet rate of CO are 3.1, 6.6, and 10.0 mL min\(^{-1}\), corresponding to Faraday efficiencies of 96.9%, 98.5% and 98.0%, respectively, as shown in Table I. The corresponding electronic leak fractions are only 3.1%, 1.5%, and 2.0%, respectively. Table I also shows that the CO2 to CO product conversion efficiencies or productivities (\(\eta_{\text{prod}} = N_{\text{CO}}'/N_{\text{CO}}\), where \(N_{\text{CO}}\) is the feeding rate of CO2, which is 30 mL min\(^{-1}\) in the present work) are 10.3%, 22.0% and 33.3%, corresponding to the three operating currents, respectively.

In order to further check the stability of the Ag-GDC fuel electrode, a longer time test (compared to the test time of Fig. 7) was performed at 800°C. The SOE was operated at a constant applied voltage of 1.59 V, and the current density was recorded to evaluate its performance stability (Fig. 8). As can be seen, the current density is relatively stable during the 18-h test time, implying that performance of the SOE with the Ag-GDC electrode is stable for direct reduction of pure CO2.

The performance of the present SOE is compared with those reported in literature for reduction of CO2 with different configurations and operating conditions.16–19,39 As shown in Table II, despite the difference of the materials used for electrodes, the apparent performance of an SOE generally depends on the thickness of the electrolyte and the effective area, i.e., an SOE with smaller effective area or thinner electrolyte gives higher performance. As can be seen in Table II, among all the SOEs, those operating on pure CO2 apparently show lower minimum electrolytic voltage than that with reducing gas feeding. With relatively large effective area, the present SOE gives the lowest minimum electrolyzing voltage (or splitting voltage) and reasonable current density. As mentioned above, at higher operating voltages, the ohmic resistance, which is mainly contributed by the electrolyte, dominates the total loss of the SOE. The good performance of the

Table II. Comparison of minimum electrolytic voltage (\(V_{\text{min}}\)) and current density (\(j\)) for CO2 reduction in YSZ electrolyte SOEs under different conditions.

| Fuel electrode | Electrolyte thickness (mm) | Temperature (°C) | Effective area (cm\(^2\)) | Feeding gas | \(V_{\text{min}}\) (V) | \(j\) (A cm\(^{-2}\)) | Ref. |
|----------------|---------------------------|------------------|----------------------------|-------------|----------------|----------------|------|
| Ni-YSZ         | 0.01-0.015                | 850              | 16                         | CO/CO2 (30/70)| ~0.92           | ~0.6 (1.1 V) | 16   |
| Ni-YSZ         | 0.015                     | 800              | 1.24                        | H2/CO2 (25/75)| ~0.91           | 1.0 (1.3 V)  | 17   |
| Ni-YSZ         | 2                         | 900              | 0.13                        | CO2         | ~0.9           | ~0.6 (2 V)  | 18   |
| LSCM-YSZ       | 0.065                     | 800              | 0.35                        | CO2         | ~0.80          | 1.8 (1.5 V) | 29   |
| Cu-GDC         | 0.25                      | 750              | 2.83                        | CO/CO2 (50/50)| ~0.95           | ~0.09 (2 V) | 39   |
| Ag-GDC         | 0.13                      | 800              | 2.00                        | CO2         | 0.70           | 1.36 (2 V)  | Present |
present SOE may be further improved by reducing the thickness of the electrolyte.

Conclusions

Electrolysis of CO₂ can be performed in YSZ electrolyte-supporting SOE with Ag-GDC fuel electrode. Short term tests of the SOE at different constant currents show that the Faraday efficiency and productivity increase with the applied current, while the electrical energy conversion efficiency and the chemical energy conversion efficiency decreasing with the current. An SOE shows good stability during an 18 h CO₂ electrolysis test, demonstrating the feasibility of using Ag-GDC as the fuel electrode (cathode) of SOEs for pure CO₂ electrolysis.

Acknowledgment

This work was supported by the National Science Foundation of China (NSFC, No. 21276097).

References

1. J. P. Barton and D. G. Infeld, IEEE Trans. Energy Convers., 19(2), 441 (2004).
2. H. Ibrahim, A. Ilincic, and J. Perron, Renew. Sust. Energ. Rev., 12(5), 1121 (2008).
3. A. Hauch, S. D. Ebbesen, S. H. Jensen, and M. Mogensen, J. Mater. Chem., 18, 2331 (2008).
4. A. Brisse, J. Schefold, and M. Zahid, Int. J. Hydrogen Energy, 33(20), 5375 (2008).
5. C. Graves, S. D. Ebbesen, M. Mogensen, and K. Lackner, Renew. Sust. Energ. Rev., 15(1), 1 (2011).
6. E. Erdle, W. Dömitz, R. Schamm, and A. Koch, Int. J. Hydrogen Energy, 17(10), 917 (1992).
7. K. Eguchi, T. Hatagishi, and H. Arai, Solid State Ionics, 86–88, 1245 (1996).
8. M. Ni, M. K. H. Leung, and D. Y. C. Leung, Int. J. Hydrogen Energy, 33(9), 2337 (2008).
9. S. D. Kim, J. H. Yu, D. W. Seo, I. S. Han, and S. K. Woo, Int. J. Hydrogen Energy, 37(1), 78 (2012).
10. J. E. O’Brien, C. M. Stoots, J. S. Herring, and J. Hartvigsen, J. Fuel Cell Sci. Tech., 3(2), 213 (2006).
11. J. S. Herring, J. E. O’Brien, C. M. Stoots, G. L. Hawkes, J.J. Hartvigsen, and M. Shahnam, J. Int. Hydrogen Energy, 32(4), 440 (2007).
12. C. H. Yang, A. Coffin, and F. L. Chen, J. Int. Hydrogen Energy, 35(8), 3221 (2010).
13. G. Tao, K. R. Sridhar, and C. L. Chan, Solid State Ionics, 175(1), 615 (2004).
14. G. Tao, K. R. Sridhar, and C.L. Chan, Solid State Ionics, 175(1), 621 (2004).
15. R. D. Green, C. C. Liu, and S. B. Adler, Solid State Ionics, 179(17), 647 (2008).
16. S. D. Ebbesen and M. Mogensen, J. Power Sources, 193(1), 349 (2009).
17. Z. L. Zhan and L. Zhao, J. Power Sources, 195(21), 7250 (2010).
18. X. L. Yue and J. T. S. Irvine, J. Electrochem. Soc., 159(8), F442 (2012).
19. X. L. Yue and J. T. S. Irvine, Electrochem. Solid-state lett., 15(3), B31 (2012).
20. R. J. Lim, M. Xie, M. A. Sk, J. M. Lee, A. Fisher, X. Wang, and K. H. Lim, Catal. Today, 233, 169 (2014).
21. K. R. Sridhar and B. T. Vaniman, Solid State Ionics, 93(3–4), 321 (1997).
22. J. E. O’Brien, M. G. McKellar, C. M. Stoots, J. S. Herring, and G.L. Hawkes, Int. J. Hydrogen Energy, 34(9), 4216(2009).
23. C. Graves, S. D. Ebbesen, and M. Mogensen, Solid State Ionics, 192(1), 398 (2011).
24. Q. Fu, C. Mabilat, M. Zahid, A. Brisse, and L. Gautier, Energy. Environ. Sci., 3(10), 1382 (2010).
25. C. Stoots, J. O’Brien, and J. Hartvigsen, Int. J. Hydrogen Energy, 34(9), 4208 (2009).
26. J. Richter, AIAA 16th Thermophysics Conference, AIAA 81-1175, p. 1 (1981).
27. J. Mizusaki, H. Tagawa, Y. Miyaki, S. Yamauchi, K. Pueki, I. Koshiro, and K. Hirano, Solid State Ionics, 53-56, 126 (1992).
28. O. Costa-Nunes, R. J. Grote, and J. M. Vohs, J. Power Sources, 141(2), 241 (2005).
29. F. Bidraun, G. Kim, G. Gorre, J. T. S. Irvine, J. M. Vohs, and R. J. Gorte, Electrochem. Solid-State Lett., 11(9), B147 (2008).
30. S.S. Xu, S.S. Li, W.T. Yao, D.H. Dong, and K. Xie, J. Power Sources, 230, 115 (2013).
31. S. S. Li, Y. X. Li, Y. Gan, K. Xie, and G. Y. Meng, J. Power Sources, 218, 244 (2012).
32. F. Y. Wang, S. Cheng, and B. Z. Wan, Catal. Commun., 9(7), 1595 (2008).
33. Y. B. Tang and J. Liu, Int. J. Hydrogen Energy, 35(20), 11188 (2010).
34. Y. H. Bai, J. Liu, H. B. Gao, and C. Jin, J. Alloys and Compounds, 480(2), 554 (2009).
35. Y. Liu, Y. H. Bai, and J. Liu, J. Electrochem. Soc., 160(1), F13 (2013).
36. J. Liu, W. H. Su, Z. Lv, Y. Ji, L. Pei, W. Liu, and T. M. He, Chinese Patent: CN02133049.2.
37. F. A. Kröger and H. J. Vink, Solid State Phys., 3, 307 (1956).
38. T. Yamamoto, D. A. Tryk, A. Fujishima, and H. Ohata, Electrochim. Acta, 47(20), 3327 (2002).
39. C. Y. Cheng, G. H. Kelsall, and L. Kleiminger, J. Appl. Electrochem., 43(11), 1131 (2013).