

Boost Steam-Tolerance and Electrochemical Performance of $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta}$ -based Air Electrode for Protonic Ceramic Electrochemical Cells

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$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta}$ (LSCF) is the state-of-the-art air electrode material for solid oxide electrochemical cells using oxide-ion electrolyte, yet its application in proton ceramic electrochemical cells (PCCs) remains limited, mainly attributed to its instability under operating conditions of high temperature and high humidity. To address this issue, coating a $\text{PrCoO}_{3-\delta}$ (PCO) catalyst onto the LSCF scaffold has been evaluated in this study. The introduction of the PCO coating not only enhances the LSCF electrode's electrochemical performance but also significantly improves its steam-tolerance by preventing direct contact between steam and LSCF. PCC single cell with PCO-coated LSCF air electrode exhibited a peak power density of 1.14 W cm^{-2} in the fuel cell mode and a current density of 2.04 A cm^{-2} at an applied voltage of 1.3 V in the electrolysis cell mode at $650 \text{ }^\circ\text{C}$. Furthermore, single cells demonstrated excellent durability under operating conditions of high temperature and high humidity, maintaining stable operation for over 1100 h at a current density of -0.5 A cm^{-2} in humid air at $600 \text{ }^\circ\text{C}$. This research highlights the potential of surface modification on LSCF as promising air electrode in PCCs to achieve efficient and stable operations.

1. Introduction

The high-quality development of contemporary society relies heavily on the efficient utilization of renewable energy sources, including solar energy, wind energy, and tidal energy. These sources, however, introduce challenges due to their inherent intermittency and variability, which can strain existing electrical equipment and energy systems.¹ Solid oxide cells (SOCs) are a new type of energy conversion device capable of efficiently converting electrical and chemical energy. Their development and research hold significant importance for integrating renewable energy into power systems. However, the high operating temperatures associated with SOCs result in high system costs and complexity, substantial thermal stress on components, and degradation of critical materials.^{2, 3} Consequently, steering the development of SOCs towards mid-low temperature operation has become crucial for their commercial viability. Proton ceramic cells (PCCs), a novel subset of SOCs, operate based on proton conduction.^{4, 5} Thanks to the lower transmission barrier of protons, PCCs can deliver higher output performance at mid-low temperatures. Additionally, the relatively dry environment at the fuel electrode mitigates the issue of Ni migration/oxidation.⁶⁻⁸ Recently, PCCs have emerged as a focal point of research, underscoring their pivotal role in enabling mid-low temperature operation for SOCs.

In the proton ceramic fuel cell (PCFC) mode, steam is generated on the air electrode side; while in the proton ceramic electrolysis cell (PCEC) mode, humidified air is supplied to the air electrode side to

enable steam electrolysis. This dual functionality of PCC creates a challenging high-temperature ($400\text{-}700 \text{ }^\circ\text{C}$), high-humidity (3 vol.-%-50 vol.-%) environment for the air electrode, leading to significant stability issues. Currently, $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta}$ (LSCF) stands out as the most commercially advanced air electrode material for SOCs based on the oxide ion conducting electrolyte, primarily due to its mixed ionic-electronic conductivity (MIEC) and high catalytic activity for oxygen reduction and evolution reactions (ORR/OER).⁹⁻¹¹ The widely accepted mechanism for the formation of proton defects suggests that the presence of a significant number of oxygen vacancies is essential.^{12, 13} Given this, the abundance of oxygen vacancies in LSCF indicates its potential to maintain a certain concentration of proton defects when exposed to humid air. Moreover, the reduced operating temperatures of PCCs can alleviate Sr segregation issue typically problematic for LSCF electrodes.¹⁴ Despite these advantages, LSCF's application as an air electrode in PCCs is limited by its instability in the environment of high-humidity. Research by Liu *et al.*¹⁵ revealed that LSCF showed relatively poor tolerance to high steam concentration at $800 \text{ }^\circ\text{C}$ and caused a large decrease in cell voltage, mainly due to the gradual decomposition of LSCF induced by steam poisoning. Research by Niania *et al.*¹⁶ indicated that the presence of water significantly exacerbated the Sr segregation process on the LSCF surface.

To enhance the durability of LSCF for use in PCCs in challenging high-temperature, high-humidity environments, researchers have been exploring various strategies.^{10, 17} Among these, surface modification and nanostructure engineering have emerged as particularly reliable and effective approaches.¹⁸⁻²² Zhou *et al.*⁹ have made significantly strides by introducing a barium cobalt oxide catalyst coating to conventional LSCF, notably improving the ORR and OER kinetics and stability and allowing for continuous operation over 1100 h at $600 \text{ }^\circ\text{C}$ with an electrolysis current density of -1 A cm^{-2} in the presence of $3\% \text{ H}_2\text{O}$. Building on this approach, Niu *et al.*¹⁰ further advanced the field by modifying LSCF air electrode with $\text{Pr}_{1-x}\text{Ba}_x\text{CoO}_{3-\delta}$ nano-films and $\text{BaCoO}_{3-\delta}$ nanoparticles. This modification enabled single cells with the enhanced air electrode to successfully operate for 300 h in an atmosphere of $3\% \text{ H}_2\text{O}$ - $97\% \text{ air}$ at $600 \text{ }^\circ\text{C}$. In

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another innovative development, Niu *et al.*¹¹ applied a highly efficient multiphase coating $\text{Ba}_{1-x}\text{Co}_{0.7}\text{Fe}_{0.2}\text{Nb}_{0.1}\text{O}_{3-\delta}$ to LSCF air electrode, resulting in a composite electrode with remarkably low polarization resistance ($0.048 \Omega \text{ cm}^2$ at 650°C), demonstrating superior steam- and Cr-tolerance, and maintaining a degradation rate of merely $0.05\% \text{ h}^{-1}$ under the demanding conditions of 650°C and 0.25 A cm^{-2} .

$\text{PrCoO}_{3-\delta}$ (PCO) is a perovskite oxide without alkaline earth metal elements, possessing MIEC property and high stability.²³⁻²⁵ It also demonstrates excellent ORR/OER activity, making it a highly active air electrode for SOCs. However, the high thermal expansion coefficient of PCO ($20.1 \times 10^{-6} \text{ K}^{-1}$)²⁶ still increases the risk of its detachment from the electrolyte surface after long-term operation. PCO is typically used as a surface coating to modify the electrode to prevent direct contact with the electrolyte. Liu *et al.*²⁷ infiltrated high-conductivity PCO onto the $\text{Pr}_{0.5}\text{Ba}_{0.5}\text{Co}_{0.7}\text{Fe}_{0.2}\text{Ti}_{0.1}\text{O}_{3-\delta}\text{Gd}_{0.2}\text{Ce}_{0.8}\text{O}_{2-\delta}$ (PBCFT-GDC) electrode and found that PCO extends the triple-phase boundary, facilitating oxygen spillover at the PCO/PBCFT-GDC interface, thereby enhancing OER activity and CO_2 electrolysis performance. To address the challenge of LSCF's instability in high-humidity environments, a PCO nanocoating was introduced onto the surface of LSCF *via* a solution infiltration method in this study. It is worth noting that this is the first report of PCO as a nano-modification layer of PCC air electrode. This modification aimed to boost the catalytic activity and durability of LSCF under the operational conditions of practical PCCs. Remarkably, single cells with the PCO-LSCF air electrode achieved a peak power density of 1.14 W cm^{-2} and a current density of 2.04 A cm^{-2} at 1.3 V in PCFC and PCEC modes at 650°C , respectively. Most notably, Single cells demonstrated stable operation for over 1100 h in the PCEC mode. These findings offer valuable insights for the commercial utilization of LSCF air electrode in PCCs.

2. Experimental

2.1 Material Synthesis

$\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_{3-\delta}$ (LSCF) powder was synthesized using a sol-gel method. Stoichiometric amounts of $\text{La}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$, $\text{Sr}(\text{NO}_3)_2$, $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, and $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were completely dissolved in deionized water. To this solution, citric acid monohydrate (CA) was added and the mixture was heated and stirred continuously until it became a clear and transparent solution. Subsequently, an ethylenediaminetetraacetic acid (EDTA)-ammonia solution was added slowly, maintaining the molar ratio of metal cations to EDTA to CA at $1:1:1.5$. The pH value of the mixture was then adjusted to $7-8$ using ammonia, and the solution was thoroughly stirred at 85°C to form a gel. The gel was baked in an electric furnace for $2-3 \text{ h}$ to yield a black fluffy precursor powder. After grinding this precursor powder, it was calcined at 800°C for 5 h to obtain the LSCF powder.

For modifying the LSCF scaffold, a PrCoO_3 (PCO) precursor solution with a concentration of 0.1 M was prepared. The solution used a solvent mixture of deionized water and isopropanol in a $1:4$ volume ratio. Stoichiometric amounts of $\text{Pr}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ were dissolved in the mixed solvent. Following complete dissolution, CA was added. The EDTA-ammonia solution was then slowly added, and the pH of the mixed solution was adjusted to ~ 7 using ammonia. The molar ratio of metal cations to EDTA to CA was kept at $1:1:1.5$.

After continuous stirring and complexation for 5 h , the PCO precursor solution was obtained. The LSCF powder was added to the PCO precursor solution with a weight ratio of PCO:LSCF of $15:100$, and sonicated for 30 min . The mixture was then placed in an oven at 80°C until the solution completely dried. Subsequently, the mixed powder was heat-treated at 800°C for 2 h to obtain PCO-coated LSCF powder.

2.2 Cell Fabrication

Symmetric cells with a cell configuration of $\text{LSCF} \mid \text{BaZr}_{0.4}\text{Ce}_{0.4}\text{Y}_{0.1}\text{O}_{3-\delta}$ (BZCYYb, $\sim 0.48\text{mm}$)|LSCF were prepared using a die-pressing, sintering, printing, and heat-treatment process. Commercial BZCYYb powder (Marion Technologies) was shaped into green discs through die-pressing. These discs were then subjected to a sintering process at 1450°C for 6 h for densification. Subsequently, LSCF paste was printed on both sides of the BZCYYb electrolyte, followed by a heat-treatment at 1000°C for 2 h to obtain LSCF symmetric cells with an effective area of 0.2 cm^2 . To prepare PCO-LSCF symmetric cells, $3 \mu\text{L}$ of PCO precursor solution was slowly infiltrated into the LSCF electrodes each time, followed by a heat-treatment at 600°C for 2 h until the loading reaching 15 wt.\% . Finally, the PCO-LSCF symmetric cells were obtained after calcination at 800°C for 2 h .

The fabrication of PCC single cells with a cell configuration of $\text{NiO} \mid \text{BZCYYb} \mid \text{PCO-LSCF}$ was achieved through a comprehensive process that included die-pressing, dip-coating, co-sintering, printing, and heat-treatment. The initial step involved the thorough wet-milling of various raw materials, including NiO, BZCYYb, corn starch, fish oil, and polyvinyl butyral, in a specific mass ratio of $12:8:4:0.05:0.5$. After drying, the mixed powder was shaped into green discs through die-pressing and then pre-sintered at 900°C for 2 h . The BZCYYb electrolyte solution, whose preparation process is detailed in a previous work²⁸, was then dip-coated onto the fuel electrode support substrate and sintered at 1450°C for 6 h . This process resulted in a half-cell with an electrolyte layer $\sim 12 \mu\text{m}$ thick. LSCF paste was then printed on the electrolyte surface, followed by a heat-treatment at 1000°C for 2 h to obtain the final PCC single cell. The method for preparing the PCO-LSCF air electrode is the same as that used in the symmetric cells.

2.3 Electrochemical Characterizations

The oxygen surface exchange coefficient (k_{chem}) and oxygen bulk diffusion coefficient (D_{chem}) were measured using the electrical conductivity relaxation (ECR) method. An LSCF sample was processed by die-pressing the LSCF powder and then sintered at 1250°C for 4 h , obtaining a dense bar with dimensions of $26.34 \times 3.67 \times 2.36 \text{ mm}^3$. The LSCF powder was added into the PCO precursor solution and subjected to sonication for 30 min to ensure homogeneity. Following this, the mixture was placed in an oven set at 80°C until complete solvent evaporation was achieved. The resultant dried powder underwent a thermal treatment at 800°C for a duration of 2 h to synthesize the PCO-coated LSCF powder. This powder was subsequently die-pressed into bar-shaped samples and sintered at 1250°C for 4 h , yielding dense PCO-LSCF bars. The resistance of the LSCF bar was measured through a four-terminal method. Following this, the chamber's atmosphere was then switched from air to pure O_2 , recording the resistance change with a conductivity meter

(Keithley DMM7510) until the response stabilized. Subsequently, the k_{chem} and D_{chem} of the sample were fitted using Matlab software.

The electrochemical performance of both symmetric cells and single cells was evaluated employing a four-probe method. Prior to the tests, Au paste was brushed on the surface of the air electrode as a current collector. The electrochemical impedance spectrum (EIS) of symmetric cells was recorded at various temperature points using electrochemical workstation (Gamry Interface 5000E), covering a frequency range from 0.01 to 100 kHz. Humid air (3/10/20/30% H₂O) at a flow rate of 25 sccm was fed to the air electrode. Single cells were tested in both PCFC and PCEC modes. In the PCFC mode, humidified H₂ (3% H₂O) at a flow rate of 25 sccm was supplied to the fuel electrode, while humidified air (3% H₂O) at a flow rate of 30 sccm was used as the oxidant in the air electrode. In the PCEC mode, the humidity level of the air supplied to the air electrode was adjusted to different levels (3/10/20/30% H₂O). The I-V curves and EIS at open circuit voltage (OCV) of the single cell were documented using electrochemical workstation.

2.4 Other Characterizations

The phase composition of LSCF and PCO and chemical compatibility between them were determined through X-ray analysis using a D/Max2500PC X-ray diffractometer (XRD). The microstructure of the air electrode and the single cells was observed using a field emission scanning electron microscope (Apreo S HiVac). To further validate the presence of the PCO nanocoating, particles stripped from the PCO-LSCF scaffold were characterized using a high-resolution transmission electron microscope (HRTEM, FEI Talos F200S). Complementing this, mapping analysis with an attached EDS was performed, offering elemental composition information of the nanocoating.

3. Results and discussion

3.1 Phase characterization and microstructure

As shown in Fig. 1a, the as-synthesized LSCF powder exhibits a pure simple perovskite phase structure. By calcining the PCO precursor solution at 800 °C for 2 h, a pure PCO phase structure is obtained, indicating that the PCO precursor solution can be infiltrated on the surface of the LSCF scaffold to produce a PCO phase. To verify the chemical compatibility between PCO and LSCF, the PCO-LSCF mixed powder was thermally treated at 1250 °C for 4 h in air. The XRD pattern of the thermally treated PCO-LSCF mixed powders showed only diffraction peaks from PCO and LSCF, indicating their good chemical compatibility.

Compared to the smooth LSCF scaffold (Fig. 1b), the PCO-LSCF surface presents a uniform PCO nano-film coating (Fig. 1c). To further verify the PCO's distribution on the LSCF scaffold's surface, HRTEM analysis on particles stripped from the PCO-LSCF scaffold was conducted, as shown in Fig. 1d-1h. In the EDS mapping (as shown in Fig. 1h), a clear enrichment of Pr and Co elements on the particle's top surface, with weaker signals of La, Sr, and Fe elements, providing strong evidence of PCO's presence. Moreover, PCO is uniformly distributed around the periphery of the LSCF particles. Based on the elemental distribution map, the PCO nanocoating on the particle in Fig. 1d can be roughly outlined. In the HRTEM image shown in Fig. 1e, the difference in interplanar spacing around the outline can be clearly seen. The white circled area shows an obvious interlacing of two types of crystal planes, with measured interplanar spacings of 0.2751 and 0.2605 nm, corresponding to the LSCF (110) crystal plane (2.739 Å, PDF#89-5720) and PCO (220) crystal plane (2.676 Å, PDF#25-1069), respectively. Thus, the white circled area can be determined to cover the interface between PCO and LSCF, i.e., the white outline in Fig. 1d crosses this area. The blue squared area on the left side of the white circled outline, with an interplanar spacing of 0.2767 nm, is almost identical to the LSCF (110) crystal plane, indicating that this area can be identified as LSCF. Similarly, the orange squared area can be identified as PCO. These TEM results demonstrate the PCO nano-catalyst coating can be achieved on the surface of the LSCF scaffold through solution infiltration.

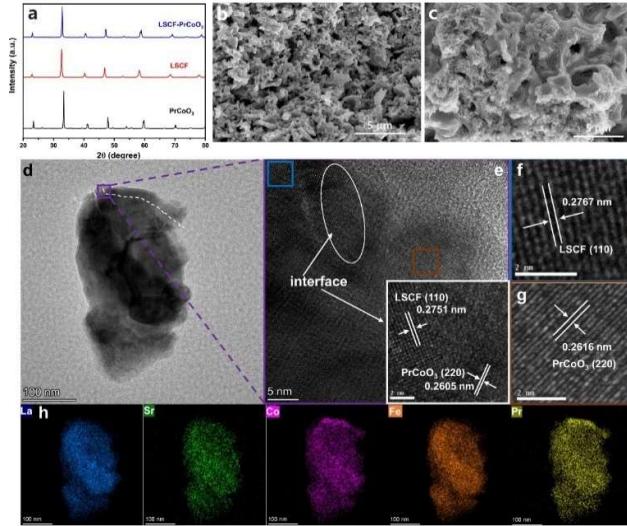


Fig.1 (a) XRD patterns of the as-prepared LSCF and PCO, as well as the PCO-LSCF mixture after heat-treatment at 1250 °C for 4 h. (b) microstructure of LSCF air electrode. (c) microstructure of PCO-LSCF air electrode. (d, e) HRTEM images of particles stripped from the PCO-LSCF electrode. (f) lattice fringe in the blue region of Fig. 1e. (g) lattice fringe in the orange region of Fig. 1e. (h) EDS mapping of the purple squared region in Fig. 1d.

3.2 k_{chem} and D_{chem} of PCO-LSCF

The ORR/OER of PCC air electrodes necessitate the transport and transfer of e^- , H^+ , and O^{2-} , underscoring the importance of high oxygen surface exchange coefficient (k_{chem}) and oxygen bulk diffusion coefficient (D_{chem}) for their ORR/OER activity. Electrical conductivity relaxation (ECR) method was employed to assess the k_{chem} and D_{chem} of both LSCF and PCO-LSCF, as shown in Fig. 2 and Fig. S1. Notably, at various temperatures, the k_{chem} and D_{chem} values for PCO-LSCF were significantly superior to those of LSCF. Specifically, at 650 °C, the k_{chem} and D_{chem} values of PCO-LSCF reached $3.10 \times 10^{-4} \text{ cm s}^{-1}$ and $3.54 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, respectively, compared with the values of $6.59 \times 10^{-5} \text{ cm s}^{-1}$ for k_{chem} and $6.59 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ for D_{chem} for LSCF, respectively. The increased k_{chem} and D_{chem} values of PCO-LSCF could be attributed to the extremely high k_{chem} and D_{chem} values of PCO, as shown in Fig. S1. Upon dissociation of oxygen molecules into oxide ions on the PCO surface, these ions traverse the thin PCO layer. Due to PCO's inherently high D_{chem} value, it effectively contributes to the increase of the D_{chem} value for the PCO-LSCF electrode. Furthermore, PCO-LSCF demonstrated outstanding oxygen surface exchange and bulk diffusion properties among different air electrodes reported in the literatures, as detailed in Table S1. These findings demonstrate that the PCO-LSCF air electrode possesses high kinetics for surface oxygen exchange process, which is a pre-requisite for promising ORR/OER catalytic activity.

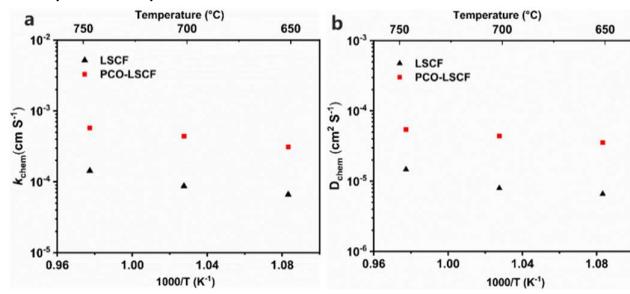


Fig. 2 k_{chem} and D_{chem} of LSCF and PCO-LSCF obtained from the ECR measurement at 650–750 °C.

3.3 Electrochemical performance of symmetrical cells

To assess the catalytic activity of the air electrodes, EIS tests were performed on symmetric cells in humid air (3% H_2O) conditions. Applying a PCO nanocoating on the surface of the LSCF led to a notable reduction in the polarization resistance (R_p), as shown in Fig. 3a and 3b. Specifically, at 700, 650, 600, and 550 °C, the R_p values were 0.062, 0.139, 0.320, and $0.786 \Omega \text{ cm}^2$ for PCO-LSCF, much lower than those for LSCF at similar testing conditions, 0.082, 0.200, 0.551, and $1.811 \Omega \text{ cm}^2$, respectively. Fig. 3c presents the Arrhenius plots for the polarization resistances of the PCO-LSCF and LSCF air electrodes, illustrating the temperature dependence of their performances. The calculated activation energy for the PCO-LSCF air electrode is 1.17 eV, markedly lower than that of the LSCF electrode at 1.42 eV. This lower activation energy suggests that the performance of the PCO-LSCF air electrode is less sensitive to temperature variations, potentially offering more stable operation under varying thermal conditions. For gain some insight into the reaction kinetics of the air electrode, EIS data obtained at 600 °C

were analysed using the distribution of relaxation time (DRT) method. This DRT analysis, illustrated in Fig. 3d, allowed for the electrochemical processes within the air electrode to be deconvoluted into several distinct peaks. These peaks were categorized into three frequency regions: low frequency (P1), medium frequency (P2), and high frequency (P3).²⁹ P1 can be associated with the gas diffusion process, P2 with the gas surface exchange and ionic bulk diffusion, while P3 with the charge transfer process.³⁰ Notably, the areas of P2 and P3 for PCO-LSCF exhibited a significant reduction when compared to that of LSCF. This reduction is attributed to the enhanced oxygen surface exchange and oxygen ion bulk diffusion facilitated by the introduction of the PCO nanocoating. Such enhancements are closely linked to the elevated k_{chem} and D_{chem} values of PCO-LSCF.

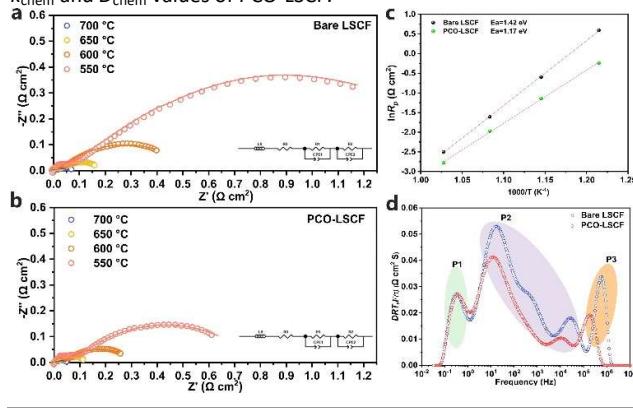


Fig. 3 (a) EIS of LSCF symmetric cell in humid air (3% H_2O) at 550–700 °C. (b) EIS of PCO-LSCF symmetric cell in humid air (3% H_2O) at 550–700 °C. (c) $\ln(R_p)$ vs $1/T$ curves of the LSCF and PCO-LSCF air electrode. (d) DRT analysis of EIS for LSCF and PCO-LSCF at 600 °C.

3.4 Electrochemical performance of single cells

The catalytic activity of LSCF is significantly enhanced with the introduction of a PCO nanocoating, as further evidenced in PCC single cells. Illustrated in Fig. 4a–4c, the cross-sectional microstructure of the single cell reveals porous electrode and a dense electrolyte layer of about 12 μm in thickness, with well bonded electrode/electrolyte interface to facilitate charge transfer. Single cells with LSCF electrode showed peak power densities of 1.01, 0.706, and 0.468 W cm^{-2} at 650, 600, and 550 °C, respectively (Fig. 4d). Introduction of PCO nanocoating on the surface of LSCF has led to increased peak power densities of 1.14, 0.803, and 0.526 W cm^{-2} at 650, 600, and 550 °C (Fig. 4e), primarily attributed to the reduced R_p value (Fig. S2). When compared to other advanced PCFC air electrodes reported in the literatures, our PCO-LSCF electrode showcases superior catalytic activity, as demonstrated by Fig. 4f and Table 1.^{31–38}

PCECs with PCO-LSCF air electrode achieved current densities of 2.04, 1.22, and 0.585 A cm^{-2} at 650, 600, and 550 °C, respectively, as shown in Fig. 4h. This contrasts with the performance of PCECs with LSCF air electrode, which only reached current densities of 1.85, 1.14, and 0.55 A cm^{-2} under similar testing conditions (Fig. 4g). Table S1 and S2 presents the current densities at various cell voltages for the single cells, illustrating the performance disparities between LSCF and PCO-LSCF air electrodes. PCO nanocoating on the surface of LSCF has led to a significant reduction in the R_p value of PCECs (Fig. S3), and the PCO-LSCF air electrode has demonstrated outstanding

performance compared to other advanced PCEC air electrodes, as shown in Fig. 4i and Table 2.^{35, 39-44}

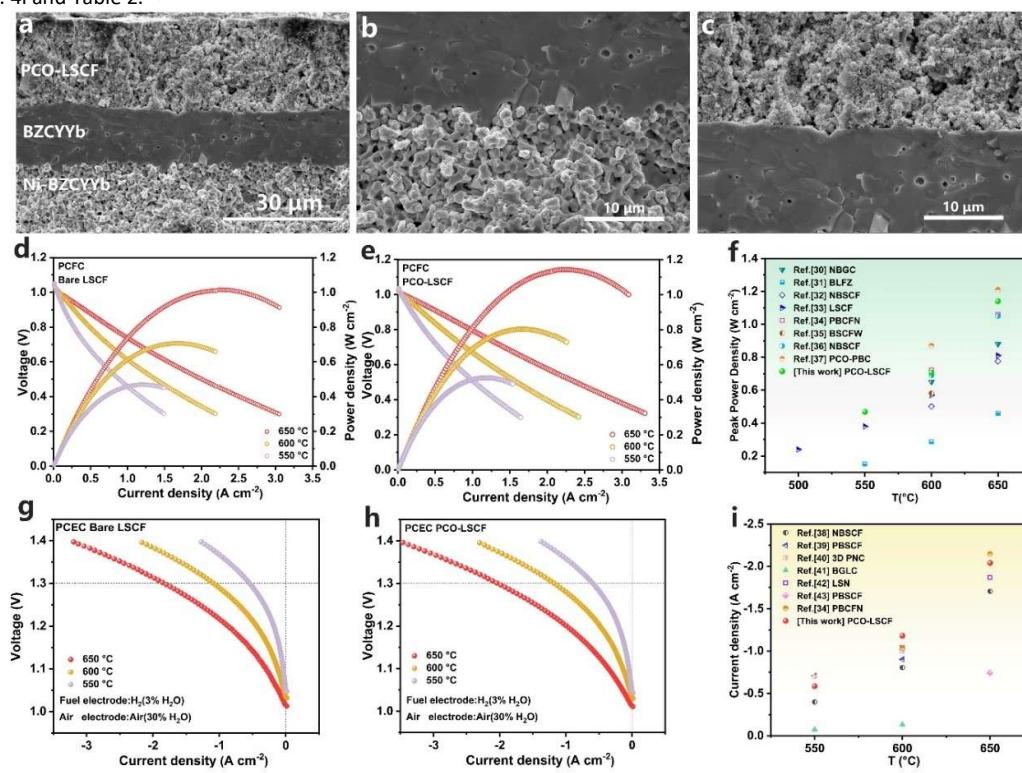


Fig.4 (a) Cross-sectional microstructure of the single cell. (b) Ni- $\text{BaZr}_{0.4}\text{Ce}_{0.4}\text{Y}_{0.1}\text{Yb}_{0.1}\text{O}_{3-\delta}$ interfacial microstructure. (c) PCO-LSCF/BZCYb interfacial microstructure; I-V curves of PCFCs with LSCF (d) and PCO-LSCF (e) air electrodes. (f) comparison of PCFC performance using PCO-LSCF air electrode with those reported in the literature. I-V curves of PCECs with LSCF (g) and PCO-LSCF (h) air electrodes. (i) comparison of PCEC performance using PCO-LSCF air electrode with those reported in the literatures.

During PCEC performance testing, the air electrode atmosphere was air containing 30% H₂O. Interestingly, variations in water vapor pressure ($p_{\text{H}_2\text{O}}$) within the air electrode appeared to have minimal impact on the current density of the electrolysis cell. Evidence from Fig. S4 indicates that, even as $p_{\text{H}_2\text{O}}$ ranged from 3% to 30%, the current density at 1.3 V maintained a steady level of about 1.4 A cm⁻² at 600 °C. An increase in $p_{\text{H}_2\text{O}}$ in the air electrode was observed to reduce the OCV (from 1.038 V to 1.032 V) of the PCEC single cell, while simultaneously causing an increase in R_p value (Fig. S4). The concurrent effects of these changes in $p_{\text{H}_2\text{O}}$ do not markedly influence the electrolysis performance. Following this, a comprehensive evaluation of the performance of LSCF symmetric cells subjected to different $p_{\text{H}_2\text{O}}$ was conducted (Fig. S5 and S6). Our observations indicate that a rise in $p_{\text{H}_2\text{O}}$ consistently results in increased R_p value of the air electrode. While humid conditions promote the formation of protonic defects and enhance proton migration, the excessive absorption of H₂O diminishes the oxygen adsorption on the surface of air electrode, consequently leading to elevated R_p . Differential EIS analysis (Fig. S7) revealed that $p_{\text{H}_2\text{O}}$ predominantly impacts the P1 and P2 processes, namely the gas diffusion and the oxygen surface exchange processes. It is also noteworthy that increasing $p_{\text{H}_2\text{O}}$ within the air electrode significantly boosts the Faraday efficiency of the PCEC single cell.^{21, 45, 46} Consequently, PCEC are inclined to operate under conditions of high $p_{\text{H}_2\text{O}}$ to optimize electrolysis efficiency. Nevertheless, the durability

of LSCF under conditions of high-temperature and high-humidity remains a concern.

3.5 Long-term stability and steam-tolerance of PCO-LSCF

At 650 °C and under 30% H₂O conditions, short-term tests were conducted on both LSCF and PCO-LSCF symmetric cells, with the R_p values recorded at intervals of several hours, as shown in Fig. 5a. During the 65-hour test period, the R_p value of LSCF sharply increased from 0.35 to 1.34 Ω cm², revealing a degradation rate of 0.015 Ω cm² h⁻¹, indicating LSCF's instability in a high-temperature and high-humidity environment. In contrast, the PCO-LSCF cell showed significantly improved steam-tolerance; its R_p value increased from 0.34 to 0.49 Ω cm² within 48 h, with a much lower degradation rate of 0.003 Ω cm² h⁻¹. This comparison underscores the enhanced stability of PCO-LSCF under the same testing conditions. To understand the reasons for the enhanced steam-tolerance of PCO-LSCF, LSCF and PCO-LSCF powders were subjected to a heat-treatment at 750 °C for 72 h in a 50%H₂O-50%air atmosphere. Subsequent XRD characterization revealed that LSCF exhibited a small amount of impurity phases (SrFeO_{2.71}, La₃Co₃O₈, La_{0.6}Sr_{0.4}FeO₃) following the hydrolysis treatment (Fig. S8). Additionally, phase instability was observed in the three strong diffraction peaks between 55-80°. These findings further confirm LSCF's instability under high-temperature and high-humidity environment, which is

consistent with the observed sharp increase in R_p value of the LSCF symmetric cells. In contrast, there is no observable impurity peaks for the PCO-LSCF powders after the hydrolysis treatment, highlighting the enhanced chemical stability of PCO-LSCF, which effectively prevents direct contact between LSCF and steam, thereby significantly enhancing the steam-tolerance of LSCF.

To further verify the steam-tolerance of PCO-LSCF, long-term stability tests were carried out on PCECs with PCO-LSCF air electrode. During a 1128-hour test at 600 °C with a steam concentration of 3% H_2O in the air electrode, and $-0.5 A\text{ cm}^{-2}$ (Fig. 5b), the single cell with a PCO-LSCF air electrode demonstrated remarkable stability, with no observable voltage degradation in 1128 h testing. This stability was maintained even when the steam concentration in the air electrode was increased to 30%, underlining the robustness of the PCO-LSCF electrode (Fig. 5c). Furthermore, in a 128-hour PCFC/PCEC cycling test at 600 °C, which involved switching the cell between 0.7 V and 1.3 V for 32 cycles (Fig. 5d), there is very stable cell performance, indicating the excellent cyclic stability of the PCO-LSCF air electrode. In contrast, the LSCF air electrode suffered notable performance degradation under similar conditions. Short-term electrolysis testing at 3% H_2O led to a noticeable voltage increase within just 60 h, with a degradation rate reaching 0.019%/h (Fig. S9a). EIS further highlighted the stability of the cell's ohmic impedance and the gradual increase in polarization impedance over time (Fig. S9b), suggesting that LSCF's hydrolysis was primarily responsible for the electrolysis cell's performance degradation. The corrosion of LSCF scaffold was visibly confirmed by comparing its microstructure before and after the short-term electrolysis test (Fig. S10).

As previously mentioned, high-temperature and high-humidity atmospheres can exacerbate Sr segregation on the surface of LSCF. These segregated Sr species react with H_2O molecules in the PCC air electrode atmosphere, leading to structural damage in the LSCF phase. The stability of the LSCF air electrode is compromised in high-temperature and high-humidity atmospheres, even with a low steam concentration of 3%. Therefore, direct use of LSCF as a PCC air electrode is not advisable. Several studies have indicated that applying nanocoating on the surface of the LSCF scaffold can mitigate Sr segregation.⁴⁷⁻⁴⁹ In this study, the introduced PCO nanocoating can also partially inhibit Sr segregation in LSCF, significantly enhancing the electrode's stability. The application of a nano-coating on LSCF

scaffold results in an elevated formation energy of oxygen vacancies, consequently diminishing their concentration on the surface.^{50, 51} This reduction in surface oxygen vacancies attenuates the electrostatic interactions between the positively charged surface oxygen vacancies and the negatively charged defect $Sr_{La'}$, thus effectively mitigating the surface segregation of Sr. Therefore, the introduction of a PCO coating contributes positively to the inhibition of Sr segregation on LSCF surfaces, subsequently diminishing the chemical interaction between segregated Sr and H_2O . Additionally, PCO can physically isolate H_2O molecules from the LSCF scaffold, thereby improving the electrode's steam-tolerance. It is worth noting that the PCO nanocoating introduced by solution infiltration may not entirely cover the LSCF scaffold (Fig. 1c). Consequently, the PCO nanocoating may not completely prevent the phase decomposition of the LSCF scaffold induced by high-humidity. However, with the support of the PCO nanocoating, the Sr segregation and the adsorption of H_2O molecules on the LSCF surface can be effectively suppressed. Consequently, PCO-LSCF demonstrates significantly boosted steam-tolerance and durability.

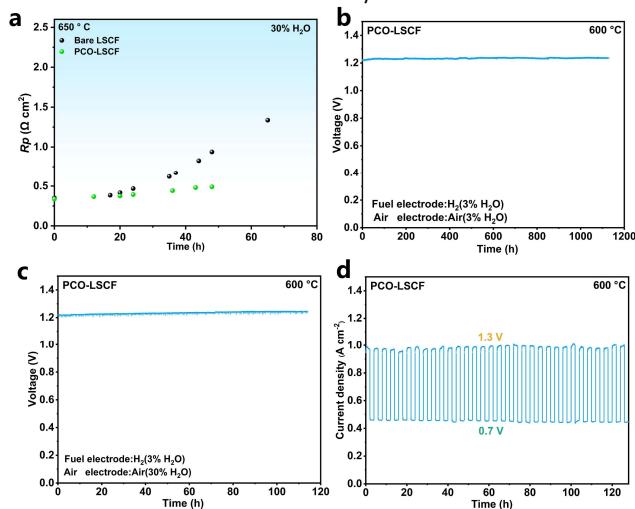


Fig. 5 (a) R_p variation over time for LSCF and PCO-LSCF symmetric cells in the air containing 30% H_2O at 650 °C. (b) durability test of a PCEC single cell with a PCO-LSCF electrode at 600 °C (3% H_2O , $J=-0.5 A\text{ cm}^{-2}$). (c) durability test of a PCEC single cell with a PCO-LSCF electrode at 600 °C (30% H_2O , $J=-0.5 A\text{ cm}^{-2}$). (d) variation of current density over time in PCFC/PCEC cycling test.

Table 1. PCFC performance comparison of this work with other reported single cells in the literatures.

| Air electrode | Electrolyte | Air electrode environment | T (°C) | PPD (W cm ⁻²) | Ref. |
|--|--------------------------|---------------------------|--------|---------------------------|-----------|
| $NdBa_{0.8}Ca_{0.2}Co_2O_{5+\delta}$ | BZCYYb4411 (15 μm) | 3% H_2O -97% Air | 600 | 0.65 | 30 |
| Zn-doped $Ba_{0.95}La_{0.05}FeO_{3-\delta}$ -BZCYYb1711 | BZCYYb1711 (10 μm) | Air | 600 | 0.286 | 31 |
| $Nd(Ba_{0.4}Sr_{0.4}Ca_{0.2})Co_{1.6}Fe_{0.4}O_{5+\delta}$ -BZCYYb1711 | BZCYYb1711 (13 μm) | Air | 600 | 0.501 | 32 |
| LSCF-BZCYYb1711 | BZCYYb1711 (14 μm) | 3% H_2O -97% Air | 600 | 0.57 | 33 |
| PrBaCo _{1.6} Fe _{0.2} Nb _{0.2} O _{5+δ} | BZCYYb1711 (10 μm) | 3% H_2O -97% Air | 600 | 0.723 | 34 |
| $Ba_{0.5}Sr_{0.5}(Co_{0.7}Fe_{0.3})_{0.6875}W_{0.3125}O_{3-\delta}$ | BZCYYb1711 (15 μm) | 3% H_2O -97% Air | 600 | 0.582 | 35 |
| $NdBa_{0.5}Sr_{0.5}Co_{1.5}Fe_{0.5}O_{5+\delta}$ | BZCYYb1711 (15 μm) | 3% H_2O -97% Air | 600 | 0.69 | 36 |
| $Pr_{0.1}Ce_{0.9}O_{2+\delta}$ -PrBaCo ₂ O _{5+δ} | BZCYYb1711 (15 μm) | 3% H_2O -97% Air | 600 | 0.87 | 37 |
| PCO-LSCF | BZCYYb4411 (12 μm) | 3% H_2O -97% Air | 600 | 0.706 | This work |

BZCYYb1711: BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-δ}; BZCYYb4411: BaZr_{0.4}Ce_{0.4}Y_{0.1}Yb_{0.1}O_{3-δ}**Table 2.** PCEC performance comparison of this work with other reported single cells in the literatures.

| Air electrode | Electrolyte | Air electrode environment | T (°C) | Current density@1.3 V (A cm ⁻²) | Ref. |
|---|---|------------------------------|--------|---|-----------|
| NdBa _{0.5} Sr _{0.5} Co _{1.5} Fe _{0.5} O _{5+δ} - BZCYYb4411 | BZCYYb4411 (14.7 μm) | 10% H ₂ O-90% Air | 600 | -0.805 | 38 |
| PrBa _{0.5} Sr _{0.5} Co _{1.5} Fe _{0.5} O _{5+δ} | BaZr _{0.8} Y _{0.2} O _{3-δ} (15 μm) | - | 600 | -0.903 | 39 |
| 3D-PrNi _{0.5} Co _{0.5} O _{3-δ} | BZCYYb4411 (10 μm) | 10% H ₂ O-90% Air | 600 | -1.000 | 40 |
| BaGd _{0.8} La _{0.2} Co ₂ O _{6-δ} | BaZr _{0.2} Ce _{0.7} Y _{0.1} O _{3-δ} (25 μm) | - | 600 | -0.131 | 41 |
| La _{1.2} Sr _{0.8} NiO _{4-δ} - | BaCe _{0.68} Zr _{0.1} Y _{0.1} Yb _{0.1} Cu _{0.02} O _{3-δ} | 20% H ₂ O-80% Air | 600 | -1.04 | 42 |
| BaCe _{0.68} Zr _{0.1} Y _{0.1} Yb _{0.1} Cu _{0.02} O _{3-δ} | (13 μm) | 20% H ₂ O-80% Air | 600 | -1.04 | 42 |
| PrBa _{0.5} Sr _{0.5} Co _{1.5} Fe _{0.5} O _{5+δ} - BZCYYb1711 | BZCYYb1711 (15 μm) | 40% H ₂ O-60% Air | 650 | -0.743 | 43 |
| PrBaCo _{1.6} Fe _{0.2} Nb _{0.2} O _{5+δ} | BZCYYb1711 (10 μm) | 3% H ₂ O-97% Air | 600 | -1.036 | 34 |
| PCO-LSCF | BZCYYb4411 (12 μm) | 30% H ₂ O-70% Air | 600 | -1.18 | This work |

4 Conclusions

In summary, a PCO nanocoating was successfully applied on the surface of the LSCF scaffold through solution infiltration, notably enhancing its catalytic activity and significantly improving its stability under high-temperature and high-humidity environments. Outstanding cell performance has been achieved using PCO coated LSCF air electrode, achieving a peak cell output power density of 1.14 W cm⁻² in the fuel cell mode and a current density of 2.04 A cm⁻² at 1.3 V in the electrolysis mode at 650 °C. The remarkable improvement in electrochemical catalytic activity of PCO coated LSCF air electrode is primarily due to the enhanced k_{chem} and D_{chem} facilitated by the PCO nanocoating. Moreover, the PCO coated LSCF air electrode demonstrated excellent stability in challenging high-temperature and high-humidity environments, maintaining stable cell performance for 1128 h in the electrolysis mode. This work demonstrates high promise of PCO surface-modified LSCF as high-performance air electrode with excellent stability in high steam and high temperature environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationship that could have to influence the work report in this paper.

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Notes and references

1. A. Hauch, R. Küngas, P. Blennow, A. B. Hansen, J. B. Hansen, B. V. Mathiesen and M. B. Mogensen, *Science*, 2020, **370**, eaba6118.
2. D. J. Brett, A. Atkinson, N. P. Brandon and S. J. Skinner, *Chem. Soc. Rev.*, 2008, **37**, 1568-1578.
3. A. Ndubuisi, S. Abouali, K. Singh and V. Thangadurai, *J. Mater. Chem. A*, 2022, **10**, 2196-2227.
4. D. Kim, T. K. Lee, S. Han, Y. Jung, D. G. Lee, M. Choi and W. Lee, *Mater. Today Energy*, 2023, **36**, 101365.
5. Y. Meng, J. Gao, Z. Zhao, J. Amoroso, J. Tong and K. S. Brinkman, *J. Mater. Sci.*, 2019, **54**, 9291-9312.
6. L. Lei, J. Zhang, Z. Yuan, J. Liu, M. Ni and F. Chen, *Adv. Funct. Mater.*, 2019, **29**, 1903805.
7. J. Cao, Y. Ji and Z. Shao, *Energy Environ. Sci.*, 2022, **15**, 2200-2232.
8. F. Liu, D. Ding and C. Duan, *Adv. Sci.*, 2023, **10**, 2206478.
9. Y. Zhou, W. Zhang, N. Kane, Z. Luo, K. Pei, K. Sasaki, Y. Choi, Y. Chen, D. Ding and M. Liu, *Adv. Funct. Mater.*, 2021, **31**, 2105386.
10. Y. Niu, Y. Zhou, W. Zhang, Y. Zhang, C. Evans, Z. Luo, N. Kane, Y. Ding, Y. Chen and X. Guo, *Adv. Energy Mater.*, 2022, **12**, 2103783.
11. Y. Niu, Y. Zhou, W. Lv, Y. Chen, Y. Zhang, W. Zhang, Z. Luo, N. Kane, Y. Ding and L. Soule, *Adv. Funct. Mater.*, 2021, **31**, 2100034.
12. L. Li, J. Zhou, Z. Hu, S. Choi, G. Kim, J.-Q. Wang and L. Zhang, *J. Phys. Chem. Lett.*, 2021, **12**, 11503-11510.
13. R. Glöckner, M. Islam and T. Norby, *Solid State Ion.*, 1999, **122**, 145-156.
14. B. Koo, K. Kim, J. K. Kim, H. Kwon, J. W. Han and W. Jung, *Joule*, 2018, **2**, 1476-1499.
15. R. Liu, S. Kim, S. Taniguchi, T. Oshima, Y. Shiratori, K. Ito and K. Sasaki, *J. Power Sources*, 2011, **196**, 7090-7096.

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Journal Name

16. M. Niania, R. Podor, T. B. Britton, C. Li, S. J. Cooper, N. Svetkov, S. Skinner and J. Kilner, *J. Mater. Chem. A*, 2018, **6**, 14120-14135.
17. Z. Wang, X. Miao, X. Ye and Z. Wen, *ACS Appl. Mater. Interfaces*, 2023, **15**, 45035-45044.
18. Y. Chen, Y. Choi, S. Yoo, Y. Ding, R. Yan, K. Pei, C. Qu, L. Zhang, I. Chang and B. Zhao, *Joule*, 2018, **2**, 938-949.
19. Z. Chen, L. Jiang, S. He, C. Guan, Y. Zou, Z. Yue, N. Ai, Y. Shao and K. Chen, *Appl. Catal., B*, 2022, **305**, 121056.
20. Y. Zhou, E. Liu, Y. Chen, Y. Liu, L. Zhang, W. Zhang, Z. Luo, N. Kane, B. Zhao and L. Soule, *ACS Energy Lett.*, 2021, **6**, 1511-1520.
21. T. Hu, F. Zhu, J. Xia, F. He, Z. Du, Y. Zhou, Y. Liu, H. Wang and Y. Chen, *Adv. Funct. Mater.*, 2023, **33**, 2305567.
22. Z. Liu, Y. Lin, H. Nie, D. Liu, Y. Li, X. Zhao, T. Li, G. Yang, Y. Sun and Y. Zhu, *Adv. Funct. Mater.*, 2024, **34**, 2311140.
23. Y. Li, W. Zhang, Y. Zheng, J. Chen, B. Yu, Y. Chen and M. Liu, *Chem. Soc. Rev.*, 2017, **46**, 6345-6378.
24. Y. Chen, W. Zhou, D. Ding, M. Liu, F. Ciucci, M. Tade and Z. Shao, *Adv. Energy Mater.*, 2015, **5**, 1500537.
25. H. Wang, G. Li, X. Guan, M. Zhao and L. Li, *Phys. Chem. Chem. Phys.*, 2011, **13**, 17775-17784.
26. R. Thakur, R. K. Thakur and N. Gaur, *J. Alloys Compd.*, 2016, **661**, 257-267.
27. Q. Liu, R. Li, W. Feng, J. Li, X. Zhang, H. Lv, Y. Shen, Y. Song, G. Wang and X. Bao, *ACS Appl. Energy Mater.*, 2022, **5**, 11604-11612.
28. P. Qiu, L. Wu, K. Cheng, S. Wu, H. Qi, C. Xiong and B. Tu, *Int. J. Hydrogen Energy*, 2023, **48**, 27805-27813.
29. M. Plekhanov, A. Kuzmin, E. Tropin, D. Korolev and M. Ananyev, *J. Power Sources*, 2020, **449**, 227476.
30. Z. Liu, Y. Chen, G. Yang, M. Yang, R. Ji, Y. Song, R. Ran, W. Zhou and Z. Shao, *Appl. Catal., B*, 2022, **319**, 121929.
31. Y. Wang, H. Zhang, J. Cao, K. Xu, K. Pei and Y. Chen, *J. Power Sources*, 2022, **524**, 231101.
32. J. Jing, Z. Lei, Z. Zheng, H. Wang, Z. Yang and S. Peng, *Int. J. Hydrogen Energy*, 2022, **47**, 35449-35457.
33. J. Chen, J. Li, L. Jia, I. Moussa, B. Chi, J. Pu and J. Li, *J. Power Sources*, 2019, **428**, 13-19.
34. H. Shimada, Y. Yamaguchi, H. Sumi and Y. Mizutani, *Ceram. Int.*, 2021, **47**, 16358-16362.
35. K. Xu, H. Zhang, Y. Xu, F. He, Y. Zhou, Y. Pan, J. Ma, B. Zhao, W. Yuan and Y. Chen, *Adv. Funct. Mater.*, 2022, **32**, 2110998.
36. D. Hu, J. Kim, H. Niu, L. M. Daniels, T. D. Manning, R. Chen, B. Liu, R. Feetham, J. B. Claridge and M. J. Rosseinsky, *J. Mater. Chem. A*, 2022, **10**, 2559-2566.
37. J. Kim, S. Sengodan, G. Kwon, D. Ding, J. Shin, M. Liu and G. Kim, *ChemSusChem*, 2014, **7**, 2811-2815.
38. K. Pei, S. Luo, F. He, J. Arbiol, Y. Xu, F. Zhu, Y. Wang and Y. Chen, *Appl. Catal., B*, 2023, **330**, 122601.
39. J. Kim, A. Jun, O. Gwon, S. Yoo, M. Liu, J. Shin, T.-H. Lim and G. Kim, *Nano Energy*, 2018, **44**, 121-126.
40. C. Duan, R. Kee, H. Zhu, N. Sullivan, L. Zhu, L. Bian, D. Jennings and R. O'Hare, *Nat. Energy*, 2019, **4**, 230-240.
41. H. Ding, W. Wu, C. Jiang, Y. Ding, W. Bian, B. Hu, P. Singh, C. J. Orme, L. Wang and Y. Zhang, *Nat. Commun.*, 2020, **11**, 1907.
42. E. Vøllestad, R. Strandbakke, M. Tarach, D. Catalán-Martínez, M.-L. Fontaine, D. Beeaff, D. R. Clark, J. M. Serra and T. Norby, *Nat. Mater.*, 2019, **18**, 752-759.
43. C. Sun, S. Yang, Y. Lu, J. Wen, X. Ye and Z. Wen, *J. Power Sources*, 2020, **449**, 227498.
44. H. Bai, Y. Zhang, J. Chu, Q. Zhou, H. Lan and J. Zhou, *ACS Appl. Mater. Interfaces*, 2023, **15**, 38581-38591.
45. F. He, S. Liu, T. Wu, M. Yang, W. Li, G. Yang, F. Zhu, H. Zhang, K. Pei and Y. Chen, *Adv. Funct. Mater.*, 2022, **32**, 2206756.
46. F. He, Y. Zhou, T. Hu, Y. Xu, M. Hou, F. Zhu, D. Liu, H. Zhang, K. Xu and M. Liu, *Adv. Mater.*, 2023, **35**, 2209469.
47. J. Li, X. Zhou, C. Wu, L. Zhao, B. Dong, S. Wang and B. Chi, *Chem. Eng. J.*, 2022, **438**, 135446.
48. D. Zeng, K. Xu, F. Zhu and Y. Chen, *Int. J. Hydrogen Energy*, 2023, **48**, 23992-24001.
49. Y. Yu, K. F. Ludwig, J. C. Woicik, S. Gopalan, U. B. Pal, T. C. Kaspar and S. N. Basu, *Appl. Mater. Interfaces*, 2016, **8**, 26704-26711.
50. J. Huang, F. Liang, S. Zhao, L. Zhao, N. Ai, S. P. Jiang, X. Wang, H. Fang, Y. Luo and K. Chen, *Adv. Funct. Mater.*, 2024, **34**, 2310402.
51. J. Huang, Q. Liu, L. Zhao, N. Ai, X. Wang, Y. Shao, C. Guan, H. Fang, Y. Luo and K. Chen, *Appl. Catal., B*, 2023, **321**, 122080.