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Operando Exsolved FeNi₃ Nanoparticles for Boosting Ethanol Internal Reforming in Solid Oxide Fuel Cells

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Abstract

Direct ethanol Solid Oxide Fuel Cells (SOFCs) are considered promising for power generation with high efficiency and flexibility from sustainable sources. Among the major challenges is the choice of catalytically active, chemically stable and coking tolerant fuel electrodes (anodes) for the internal reforming and oxidation of ethanol. Here, we *operando* exsolved FeNi₃ nanoparticles from Ni-doped SFM (Sr₂Fe_{1.3}Mo_{0.5}Ni_{0.2}O_{6±δ}, SFMNi) fuel electrode to significantly enhance the power output. Our analysis confirmed that Ni doping increased surface basicity and oxygen vacancy concentration which are linked to ethanol steam reforming selectivity toward dehydrogenation pathways over dehydration which was observed in the undoped SFM sample. The thermocatalytic studies showed the high ethanol reforming activity of FeNi₃ nanoparticles with intriguing coking tolerance properties as confirmed by crystallographic and Raman analyses. This resulted in an >30% enhancement in the peak power density with adequate stability. Our findings highlight the strong coupling between reforming activity and electrochemical performance, positioning nanoparticle-functionalized perovskite electrodes as a promising strategy for efficient and flexible SOFCs operating on renewable fuels.

Keywords

Solid oxide fuel cells; Ethanol steam reforming; operando exsolution; perovskite electrodes



Introduction

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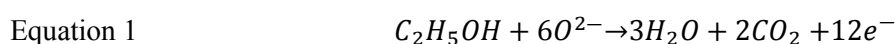
International shipping emitted approximately 1.1 million tonnes of CO₂, accounting for around 2.9% of global anthropogenic greenhouse gas emissions.¹ As maritime trade continues to expand, scalable low-carbon propulsion technologies are urgently required. Fuel cells are electrochemical energy conversion devices that directly transform chemical energy into electrical energy with high efficiency, low noise, and minimal environmental impact, as they operate with no mechanical parts and do not produce air pollutants (NO_x, SO₂, particulate matter).²

Their operating temperature depends on the type of cell. Proton exchange membrane fuel cells (PEMFC) operate at low temperatures and offer high current densities, but rely on expensive noble metal catalysts due to their acidic environment.³ They are also sensitive to impurities in the fuel stream, requiring highly purified input.⁴ The SOFC, on the other hand, operates at high temperatures (700 – 1000 °C), which allows for internal reforming, compatibility with a wide range of fuels including hydrocarbons and alcohols, and improved electrode kinetics.⁵ In SOFC, hydrogen is the typically employed fuel which is introduced and subsequently oxidized at the anode (fuel electrode) by oxide ions migrating through the ceramic electrolyte by the reduction of molecular oxygen at the cathode (air electrode).

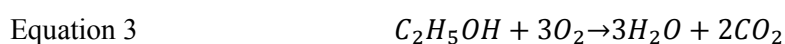
Although, hydrogen exhibits significant advantages and can be efficiently utilized in SOFCs, its low volumetric energy density necessitates high-pressure or cryogenic storage, for which the required infrastructure remains underdeveloped and cost-intensive.⁶ Alternatively, hydrogen containing fuels such as ammonia, methanol, and ethanol can be produced in a sustainable and efficient manner may offer greater compatibility with existing fuel handling and storage systems.⁵ Among these, ethanol originating from biobased processes, including that derived from second-generation lignocellulosic biomass, stands out as an intriguing option. Bioethanol is renewable, non-toxic, non-corrosive, and has a high volumetric energy density in liquid form under ambient conditions, facilitating storage and distribution using established infrastructure.

To utilize ethanol in SOFCs two possible pathways are considered, either through direct electrochemical oxidation (**Equation 1**) or via internal reforming into hydrogen (**Equation 4**), which is subsequently oxidized on the anodic electrode surface (**Equation 6**):⁷

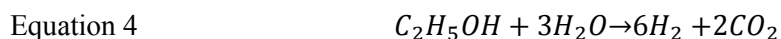
Direct ethanol oxidation:



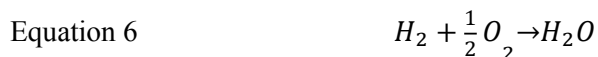
Oxygen reduction reaction (ORR):



Ethanol steam reforming (ESR):



Hydrogen oxidation reaction (HOR):



In the case of direct ethanol SOFCs (DESOFCs), the pathway is limited by the sluggish kinetics due to the complex 12 electron transfer process required for the complete oxidation, resulting in relatively low open-circuit voltages (OCV) of around ~ 0.8 V and moderate peak power densities in the range of 50–300 mW cm^{-2} .^{8–12} Moreover, incomplete oxidation often leads to the formation of intermediate species such as acetaldehyde and ethylene, which can promote carbon deposition and accelerate anode degradation.^{8–12}

Internal ethanol reforming SOFCs rely on the anodic electrocatalyst materials to efficiently convert ethanol and steam into hydrogen and carbon dioxide. Due to the hydrogen presence instead of ethanol, higher OCVs (>1.0 V) and higher peak power densities than DESOFC are enabled, hence supporting the development of more compact and lightweight SOFC systems. It is obvious that the performance is directly linked to the higher electrochemical activity of hydrogen relative to ethanol. Such behavior has previously been reported in ethanol-fueled SOFCs, where higher operating temperatures promoted ethanol decomposition, resulting in increased hydrogen formation and enhanced power densities.^{13–16} The same result can be also obtained when catalytically active electrodes for ethanol reforming are employed to allow for similar hydrogen production rates without the requirement of elevated operating temperatures which may decrease the lifetime of the SOFC.^{12, 17}

Nickel–yttria-stabilized zirconia (Ni–YSZ cermet) is the state-of-the-art anode material due to its adequate catalytic activity for hydrogen oxidation, electrical conductivity, and thermal compatibility with the ceramic electrolyte.¹⁸ However, Ni–YSZ suffers from poor redox stability due to Ni coarsening and displays less fuel flexibility, as it is prone to coking when fed with hydrocarbons such as ethanol.¹⁹ On the other hand, perovskite oxides have emerged as promising alternative anode materials due to their mixed ionic-electronic conductivity (MIEC), high redox stability, and in case of some specific compositions, enhanced tolerance to diverse fuels.^{14, 20, 21}

The catalytic performance of SOFC anodes can be further improved through the incorporation of metal nanoparticles via infiltration²² or exsolution.²³ Infiltration deposits catalytic metal nanoparticles onto the anode surface, increasing activity, but often suffers from particle agglomeration and limited thermal stability during prolonged operation. Conversely, exsolution generates metal nanoparticles that are socketed to the perovskite backbone, resulting in enhanced thermal stability, sintering resistance, and durability.²⁴ Efficient cleavage of C–C bonds is critical for converting ethanol into hydrogen and CO .²⁰



Both infiltration and exsolution facilitate this process, but exsolved nanoparticles typically provide better control over particle size and distribution,²⁵ which is essential for effective reforming and carbon deposition resistance.

Molybdenum-doped strontium ferrites ($\text{Sr}_{2.0}\text{Fe}_{1.5}\text{Mo}_{0.5}\text{O}_{6\pm\delta}$, SFM) have attracted significant research attention as fuel electrode for hydrogen oxidation, steam and/or CO_2 electrolysis in solid oxide reactors²⁶⁻²⁸ due to their significant MIEC properties.²⁹ Concurrently, various B-site doping strategies have been followed to achieve exsolution of catalytically active nanoparticles at the host SFM.^{27, 28, 30, 31} Here, we have employed a Ni-doped SFM ($\text{Sr}_{2.0}\text{Fe}_{1.3}\text{Mo}_{0.5}\text{Ni}_{0.2}\text{O}_{6\pm\delta}$, SFMNi) that allows the *operando* exsolution of Ni-Fe nanoparticles from under the reducing conditions induced by ethanol steam reforming (ESR). This approach eliminates the need for a separate pre-reduction step and yields Ni-Fe particles that modify the surface chemistry, shifting selectivity from ethanol dehydration to dehydrogenation. The in-situ generated hydrogen over Ni-Fe nanoparticles on the SFMNi fuel electrode reduces polarization resistance during SOFC operation and enhances power density compared to direct ethanol oxidation on SFM electrodes lacking catalytic active exsolved nanoparticles. These findings indicate that exsolved nanoparticles enable endothermic ethanol reforming, thereby achieving higher SOFC performance and supporting more compact SOFC designs.

Experimental

Electrode preparation

$\text{Sr}_{2.0}\text{Fe}_{1.5}\text{Mo}_{0.5}\text{O}_{6\pm\delta}$ (SFM) and $\text{Sr}_{2.0}\text{Fe}_{1.3}\text{Mo}_{0.5}\text{Ni}_{0.2}\text{O}_{6\pm\delta}$ (SFMNi) were synthesized via a modified sol-gel method using EDTA and citric acid as chelating agents. Stoichiometric amounts of $\text{Sr}(\text{NO}_3)_2$, $\text{Fe}(\text{NO}_3)_2 \cdot 9\text{H}_2\text{O}$, $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ and $\text{Ni}(\text{NO}_3)_2$ were dissolved in Milli-Q water containing EDTA and citric acid at a molar ratio of 1 : 1 : 1.5 (metal ions : EDTA : citric acid). The pH was adjusted to 9 using 25% $\text{NH}_3\text{-H}_2\text{O}$. After complete dissolution, the solution was heated to 90 °C under continuous stirring for 2 h to form a gel, which was subsequently combusted at 300 °C for 2 h (5 °C/min). The resulting ash was ground and calcined at 1100 °C for 5 h (2 °C/min) to obtain the final perovskite powders.

Scandia-stabilized zirconia (ScSZ) electrolyte substrates, gadolinium-doped ceria powder ($\text{Gd}_{0.1}\text{Ce}_{0.9}\text{O}_{1.95}$, GDC mid-grade), lanthanum strontium cobalt ferrite powder ($(\text{La}_{0.6}\text{Sr}_{0.4})_{0.95}\text{Co}_{0.20}\text{Fe}_{0.80}\text{O}_{3-\delta}$, LSCF-P), screenprint ink (α -terpineol) and gold paste were purchased from Fuel Cell Materials and used for cell fabrication. Electrolyte-supported cells with the configuration Au/SFM(Ni)-GDC/GDC/ScSZ/GDC/LSCF-GDC/LSCF were fabricated using ScSZ substrates (Fuel Cell Materials, 211214) with a 25 mm diameter and 150 μm nominal thickness. A GDC barrier layer (50:50 wt% solids: α -terpineol, 2 $\text{mg}_{\text{calcined}} \cdot \text{cm}^{-2}$) was screen printed onto both sides of the electrolyte and sintered at 1300 °C for 4 h (2 °C \cdot min⁻¹), yielding a dense layer that prevented insulating interfacial



phases and improved adhesion via enhanced surface roughness. A functional LSCF-GDC (50:50 wt%) layer (35:65 wt% solids: α -terpineol, 4 mg_{calcined}·cm⁻²) and an LSCF current collector layer (30:70 wt% solids: α -terpineol, 4 mg_{calcined}·cm⁻²) were sequentially screen printed on top. On the anode side, a functional SFM-GDC or SFMNi-GDC layer (35:65 wt% solids: α -terpineol, 4 mg_{calcined}·cm⁻²) was applied on the GDC barrier. The complete cell was sintered at 1100 °C for 2 h with a heating rate of 2 °C·min⁻¹. Gold paste was applied to the sintered anode for current collection and heated at 300 °C for 2 h to remove organic residues. Gold was assumed to be electrochemically inert towards hydrogen and ethanol oxidation. The geometric active cell area was 1 cm².

Characterisations

Structural bulk properties and phase purity were examined by powder X-ray diffraction (Bruker D8 Endeavor) using Cu K_{α1} ($\lambda = 1.5406 \text{ \AA}$) and Cu K_β ($\lambda = 1.392 \text{ \AA}$) radiation at 40 kV and 25 mA. Diffraction data were collected over a 2θ range of 20-80° with a scan rate of 1°·min⁻¹. Elemental analysis by inductively coupled plasma optical emission spectrometry (ICP-OES) was performed using a PerkinElmer Optima 7000 DV instrument to determine elemental concentration of the as-prepared SFM-based materials.

X-ray photoelectron spectroscopy (XPS) measurements were performed using a Thermo Scientific ESCALAB 250Xi equipped with monochromatic aluminum source ($K\alpha = 1486.6 \text{ eV}$). The analysis area was defined by a 650 μm spot size, with the X-ray source operated at 14.8 kV and 1.6 A. Survey spectra were collected with a pass energy of 100 eV and a step size of 1 eV, while high-resolution spectra were acquired with a pass energy of 20 eV and a step size of 0.1 eV. Charge compensation was applied by referencing the adventitious carbon C 1s peak to 284.8 eV. The spectra were processed using Thermo Avantage software, including background subtraction and peak fitting.

NH₃-TPD and CO₂-TPD measurements were carried out using an Autochem II 2920 instrument from Micromeritics. Prior to analysis, the samples (0.1 g) were pretreated at 400 °C for 60 min under a 30 sccm He flow. For NH₃-TPD, the samples were cooled to 100 °C, exposed to a 10% NH₃-He stream (30 sccm) for 60 min to saturate the surface, and then analyzed by heating from 100 to 850 °C at a rate of 10 °C min⁻¹ under pure He (30 sccm). For CO₂-TPD, the same pretreatment was applied, after which the samples were cooled to 100 °C, saturated with pure CO₂ (30 sccm) for 60 min, and subsequently analyzed from 100 to 850 °C at a rate of 10 °C min⁻¹ under pure He (30 sccm). The oxygen release from the as-prepared materials was analyzed on a Perkin Elmer TGA 4000 (Perkin Elmer, Waltham, MA, USA). TGA analyses were performed within a temperature range of 50-850 °C (heating rate 10 °C min⁻¹) in air. The oxygen vacancies of the samples were evaluated by electron paramagnetic resonance (EPR) on a Bruker A300 spectrometer at room temperature and air environment.

Electrode microstructures and spent catalyst surfaces were characterized by scanning electron microscopy (FEI Nova NanoSEM 650). Raman spectroscopy was employed to probe structural and



vibrational characteristics of the samples. Spectral acquisition utilized a Horiba XploRA-PLUS confocal Raman system featuring a 532 nm excitation source and 50x objective lens. Measurements covered the 200-1200 cm^{-1} spectral region with a spectral resolution of 2-3 cm^{-1} . All spectra underwent processing and analysis through the LabSpec6 analytical platform.

The microstructure of samples was examined with a double-corrected (probe and image correctors) and monochromated Themis Z scanning transmission electron microscope (Thermo Fisher Scientific) operating at 300 kV. The STEM images were acquired through HAADF (high-angle annular dark-field) mode and TEM images were captured using Ceta 16M camera. The beam convergence angle was measured ~ 24 mrad, and the probe current of 30-50 pA was used for STEM imaging. The TEM samples were prepared by drop-casting an ethanol suspension of the catalyst onto lacey carbon-supported copper grids, followed by transfer into the microscope using a specialized double-tilt holder optimized for x-ray collection.

Energy dispersive X-ray spectroscopy (STEM EDS maps) results were achieved with a Dual X EDS system (Bruker) using two large area detectors in total capturing 1.76 steradian with a probe current of 50 pA for more than 2 hours. Data acquisition and analysis were done using Velox software.

Thermocatalytic evaluation

Catalytic performance was evaluated in a fixed-bed quartz reactor (U-tube configuration, 6 mm of internal diameter) containing 20 mg of catalyst. The furnace temperature was increased to the reaction temperature under pure N_2 (60 mL min^{-1} flow rate). The ESR experiments were performed at 700 $^\circ\text{C}$ and 750 $^\circ\text{C}$ with a feed composition of $\text{H}_2\text{O}:\text{EtOH}$ molar ratio of 4:1 (2.6% EtOH-10.4% $\text{H}_2\text{O}-\text{N}_2$), selected to favour the water-gas shift reaction. Ethanol and water vapours were delivered to the reactor using two independent N_2 carrier streams (each at 30 mL min^{-1}), saturated by passing through temperature-controlled saturators (20 $^\circ\text{C}$ for ethanol, 59 $^\circ\text{C}$ for water). Analysis of the reactor effluent was conducted using an Agilent 7890A gas chromatograph. This instrument incorporated both a flame ionization detector (FID) and a thermal conductivity detector (TCD), coupled to molecular sieve and Plot U columns for gas separation. Ethanol conversion (X_{Ethanol}) and the product formation rates (R_x) were determined by using **equation 7** and **equation 8**, respectively.

Ethanol conversion (X_{Ethanol}) and product formation rates (R_x) were determined using Equation 7 and Equation 8, respectively. These calculations employed the inlet and outlet molar ethanol flow rates ($F_{\text{Ethanol},i}$ and $F_{\text{Ethanol},o}$), the total molar flow rate (F_{total}), the catalyst bed mass (m_{cat}), and the molar fraction of each product species (y_x).

$$\text{Equation 7} \quad X_{\text{ethanol}} = \frac{F_{\text{Ethanol},\text{in}}}{F_{\text{Ethanol},\text{out}}} \cdot 100$$

$$\text{Equation 8} \quad R_x = \frac{F_{\text{total}} \cdot y_x}{m_{\text{cat}}}$$



Electrochemical characterisation

Electrochemical measurements were performed using an Open Flanges™ setup (Fiarell Sàrl), enabling reproducible testing without ceramic sealing paste. The anode chamber was sealed by compressing the cell onto a mica ring (Thermiculite® 870, Flexitallic), while the cathode remained open to ambient air. Current collection from the anode was achieved through a gold mesh placed beneath the cell within the mica ring. A gold M_Grid™, connected to two gold wires, served as the current collector for the cathode. The wires were insulated with alumina felt to prevent short circuits. The assembly was enclosed between a Crofer 22 APU gas diffusion plate (anode) and a stainless-steel gas diffusion plate (cathode), each equipped with welded inlet/outlet tubes for gas distribution. Uniform compression was applied using four springs.

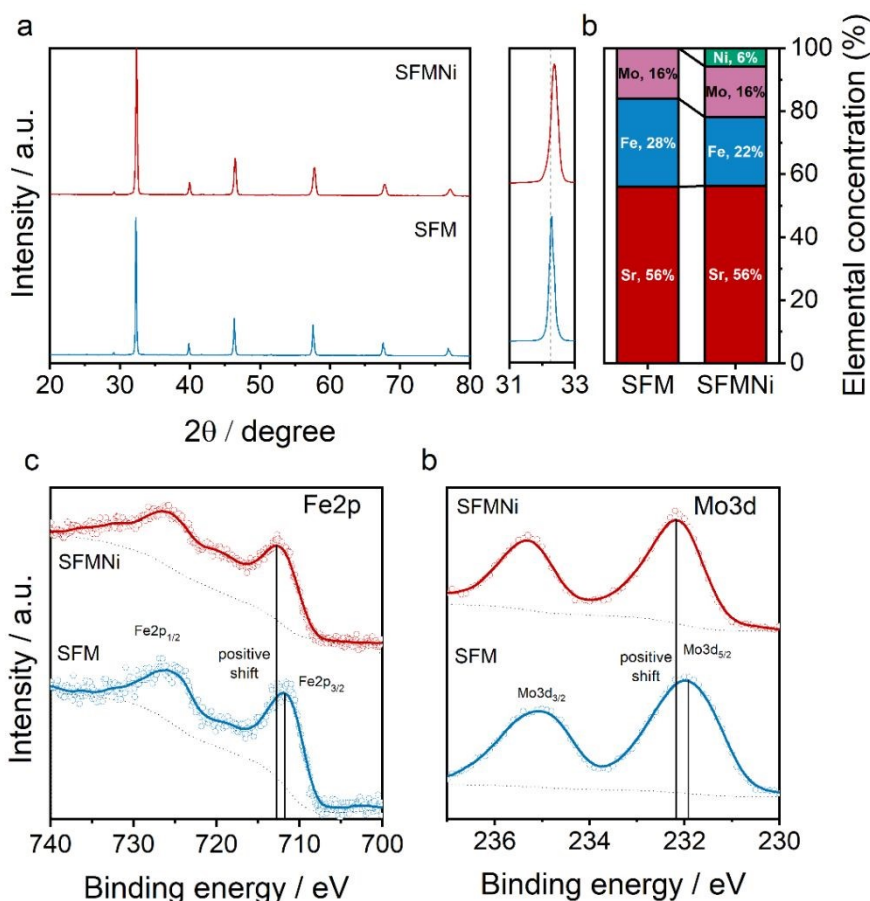
A Zahner IM6 Electrochemical Workstation was used to conduct electrochemical measurements. Linear sweep voltammetry was conducted from OCV to 0.2 V at a scan rate of 10 mV·s⁻¹. Electrochemical impedance spectroscopy (EIS) was recorded at 0.6 V under fuel cell conditions, using a frequency range of 100 kHz to 0.1 Hz and a 10 mV AC perturbation. Cell stability was evaluated by monitoring the current response at a constant voltage of 0.6 V. All measurements were conducted at 750 °C, with temperature monitored via type-K thermocouples embedded in the stainless-steel diffusion plate in contact with the cell. Air was supplied to the cathode to maintain the oxidized state of the LSCF electrode. Steam was generated by bubbling N₂ through a water reservoir maintained at 55 °C. Ethanol was introduced by bubbling a separate N₂ stream through an ethanol reservoir at 29 °C, yielding an ethanol-to-steam molar ratio of 1:4. All gas lines were heated to 120 °C to prevent condensation.

Results and Discussion

Characterisation of the as prepared samples

The composition Sr_{2.0}Fe_{1.3}Ni_{0.2}Mo_{0.5}O_{6±δ} (SFMNi) was selected alongside Sr_{2.0}Fe_{1.5}Mo_{0.5}O_{6±δ} (SFM), since Ni = 0.2 doping has been reported to yield optimal nanoparticle dispersion and stability.^{27, 28, 31} The crystal structure and purity of the as-prepared SFM and SFMNi was confirmed by XRD and ICP-OES analysis (**Figure 1a,b**). The results revealed that pure perovskite phases were achieved for both samples following the calcination process in ambient air at 1100 °C for 5 h. The magnified section of the XRD pattern indicate a shift of the SFMNi to higher 2θ angles compared to SFM, implying a decrease in lattice cell volume upon Ni doping. More specifically, in SFM the oxidation state of Fe is a mixture of Fe²⁺ (0.78 Å) and Fe³⁺ (0.645 Å) and the direct substitution of Fe²⁺ by Ni²⁺ ion (0.69 Å) could partially explain this observation. In addition, when Ni²⁺ is incorporated into the structure, Fe and Mo tend to attain higher oxidation states to maintain charge balance, thus also decreasing the cell volume.³² By carrying out XPS analysis on the samples, an increased fraction of Fe³⁺ over Fe²⁺ species for SFMNi was observed due to the positive shift of the Fe2p_{3/2} peak toward higher binding energies upon





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Figure 1. Crystallographic and compositional characterization of as-prepared SFM and SFMNi. **(a)** XRD patterns showing the effect of Ni doping, with a magnified region around 32° highlighting a rightward shift to higher angles, and **(b)** elemental weight fractions determined by ICP-OES. XPS spectra of as-prepared SFM and SFMNi of **(c)** Fe 2p and **(d)** Mo 3d regions show a positive shift in binding energy after Ni doping.

Ni doping (**Figure 1c**).¹¹ A similar effect is also observed for the Mo3d_{5/2} peak, where a positive shift to higher binding energies shows an increased fraction of Mo⁶⁺ (0.59 Å) relative to Mo⁵⁺ (0.61 Å) (**Figure 1d**).¹¹ These findings indicate that Ni doping decreases the ratio of Fe²⁺/Fe³⁺ and Mo⁵⁺/Mo⁶⁺ couples, leading to lattice shrinkage as reported for B-site cations in other perovskite systems.^{33, 34} Furthermore, XPS analysis of the Sr3d, O1s and C1s regions reveals that the as-prepared SFM surface is more extensively hydroxylated and carbonated than as-prepared SFMNi (**Figure S1**). The positive binding energy Sr 3d shift, strong O 1s ~530.5 eV peak region, and C 1s peak at ~289 eV indicate hydroxyl carbonate-rich surface on SFM,³⁵ while SFMNi shows a lower oxygen-to-cation ratio (1.38 vs 2.05), implying higher oxygen vacancy concentration on as-prepared SFMNi.³⁶

Surface acidity and oxygen defect chemistry strongly influence product selectivity during ESR. Ethanol dehydration to ethylene is promoted on acidic sites, whereas dehydrogenation to acetaldehyde is favored on basic sites.³⁷ Since ethylene readily leads to coking through oligomerization, the dehydrogenation pathway is generally preferred to stabilize ESR performance. To assess surface acid-base properties,



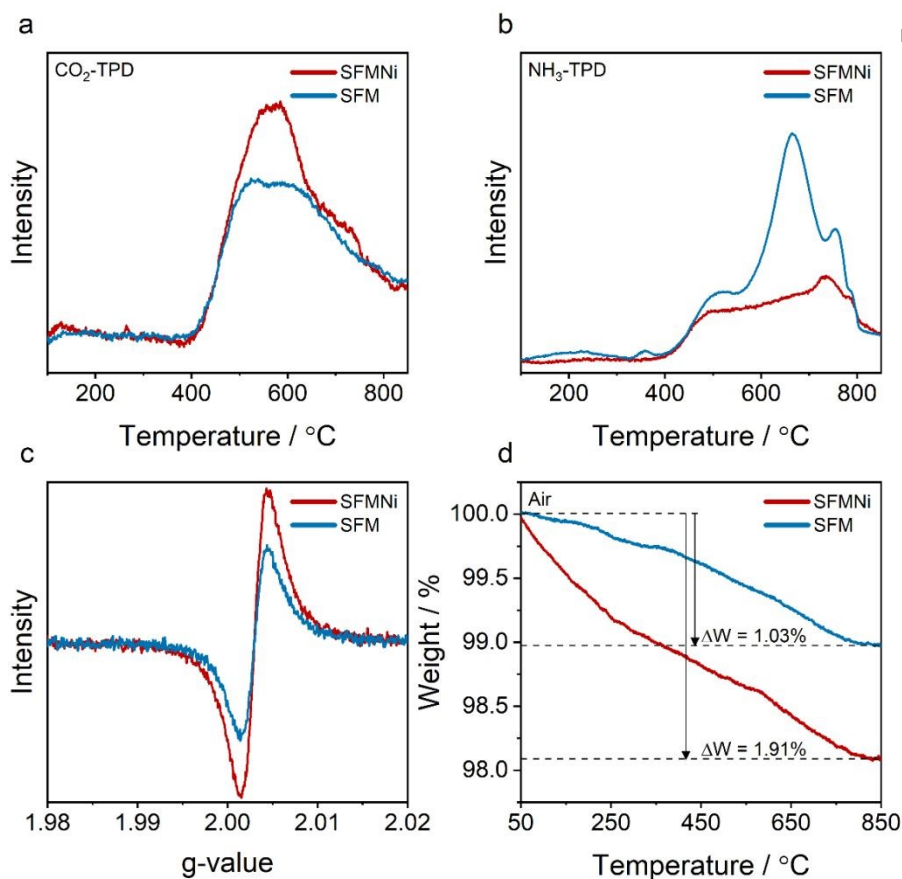


Figure 2. Characterization of surface acidity and oxygen vacancy capacity of the as-prepared SFM and SFMNi samples. **(a)** CO₂-TPD profiles demonstrating surface basicity, **(b)** NH₃-TPD profiles identifying the surface acidity, **(c)** TGA curves in air indicative of oxygen release, and **(d)** EPR spectra highlighting the relative concentration of bulk oxygen vacancies.

	Base sites μmol/g	Acid Sites μmol/g	Ratio base to acid sites
SFM	201.31	613.77	3.05
SFMNi	293.56	364.88	1.24

Table 1. Density of base and acid sites on as-prepared SFM and SFMNi powders

CO₂-TPD and NH₃-TPD measurements were carried out on SFM and SFMNi samples and the results are shown in **Figure 2**. CO₂-TPD (**Figure 2a**) revealed a higher CO₂ adsorption capacity for SFMNi, indicative of increased basicity, whereas NH₃-TPD (**Figure 2b**) showed stronger acidity for SFM relative to SFMNi. The integrated peak areas are summarized in **Table 1**, demonstrating the higher ratio of base to acid sites for SFM. This suggests that SFM may exhibit a stronger preference for ethanol dehydration over dehydrogenation compared to SFMNi. Ni doping may modify the effective surface charge, whereby acid strength correlates with the density of positively charged sites, while basic strength is associated with negatively charged surface species.³⁸ While this may be evaluated by XPS, the positive shifts toward higher binding energy of Fe2p and Mo3d spectra indicate the presence of more positively charged metal centers on as-prepared SFMNi in comparison to as-prepared SFM. This

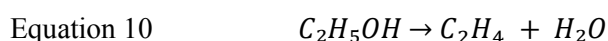
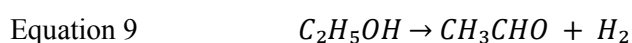


suggests that acidity measured through NH_3 -TPD may not primarily originate from a difference in cation oxidation states. However, discrepancies may arise from differences in measurement conditions between desorption techniques and XPS. Furthermore, it should be noted that conventional XPS probes several nanometers into the material and may therefore not accurately represent the composition of the outermost catalytic monolayers.³⁹

Low-temperature EPR was employed to quantify oxygen vacancies in as-prepared SFM and SFMNi, revealing a characteristic signal at a g-factor of 2.001 (**Figure 2c**). The higher intensity observed for SFMNi indicates that Ni incorporation promotes additional oxygen vacancy formation. This observation is further supported by TGA (**Figure 2d**), where the greater weight loss between 50 and 850 °C corresponds to the release of adsorbed species and lattice oxygen. Collectively, these results demonstrate that SFMNi exhibits an increased concentration of oxygen vacancies compared to SFM, suggesting reduced susceptibility to carbon deposition and a promoted steam activation.³⁷

Catalytic testing

The thermocatalytic performance of SFM and SFMNi powders was assessed in an ethanol-steam mixture (2.6% EtOH-10.4% $\text{H}_2\text{O-N}_2$) at 700 and 750 °C to examine the influence of operating temperature on exsolution behavior and to identify the optimal conditions for SOFC operation (**Figure 3**). Excess steam was selected to shift the water-gas-shift equilibrium to hydrogen formation. SFM demonstrates similar ESR performance at both 700 and 750 °C, achieving ~29% ethanol conversion after 20 h on stream and producing 1.04 and 1.08 $\text{mol}\cdot\text{min}^{-1}\cdot\text{g}_{\text{cat}}^{-1}$ of H_2 and 0.76 and 0.79 $\text{mol}\cdot\text{min}^{-1}\cdot\text{g}_{\text{cat}}^{-1}$ of acetaldehyde, respectively (**Figure 3a,b**). Furthermore, small amounts of ethylene were observed at both 700 and 750 °C over the course of time with 0.184 and 0.222 $\text{mol}\cdot\text{min}^{-1}\cdot\text{g}_{\text{cat}}^{-1}$, respectively. The low ESR activity is attributed to the absence of a metallic phase, which limits C–C bond cleavage. Consequently, hydrogen, acetaldehyde and ethylene are mainly detected in the outlet, indicating that ethanol dehydrogenation and dehydration dominate (**Equation 9,10**).



In contrast, the SFMNi sample exhibited improved catalytic activity at 700 °C compared to SFM (**Figure 3**). After 20 h, ethanol conversion reached 44%, while dominant products were measured to be acetaldehyde (1.54 $\text{mol}\cdot\text{min}^{-1}\cdot\text{g}_{\text{cat}}^{-1}$), hydrogen (2.74 $\text{mol}\cdot\text{min}^{-1}\cdot\text{g}_{\text{cat}}^{-1}$), CO (0.48 $\text{mol}\cdot\text{min}^{-1}\cdot\text{g}_{\text{cat}}^{-1}$) and to a lesser extent ethylene (0.168 $\text{mol}\cdot\text{min}^{-1}\cdot\text{g}_{\text{cat}}^{-1}$). Minor CO formation indicates limited ethanol steam reforming and a weak contribution from metallic sites, confirming ethanol dehydrogenation as the dominant pathway (**Equation 9**). The enhanced activity may be attributed to Ni doping, facilitating oxygen vacancy formation in reductive conditions and increasing surface basicity for ethanol dehydrogenation.^{27, 40, 41}



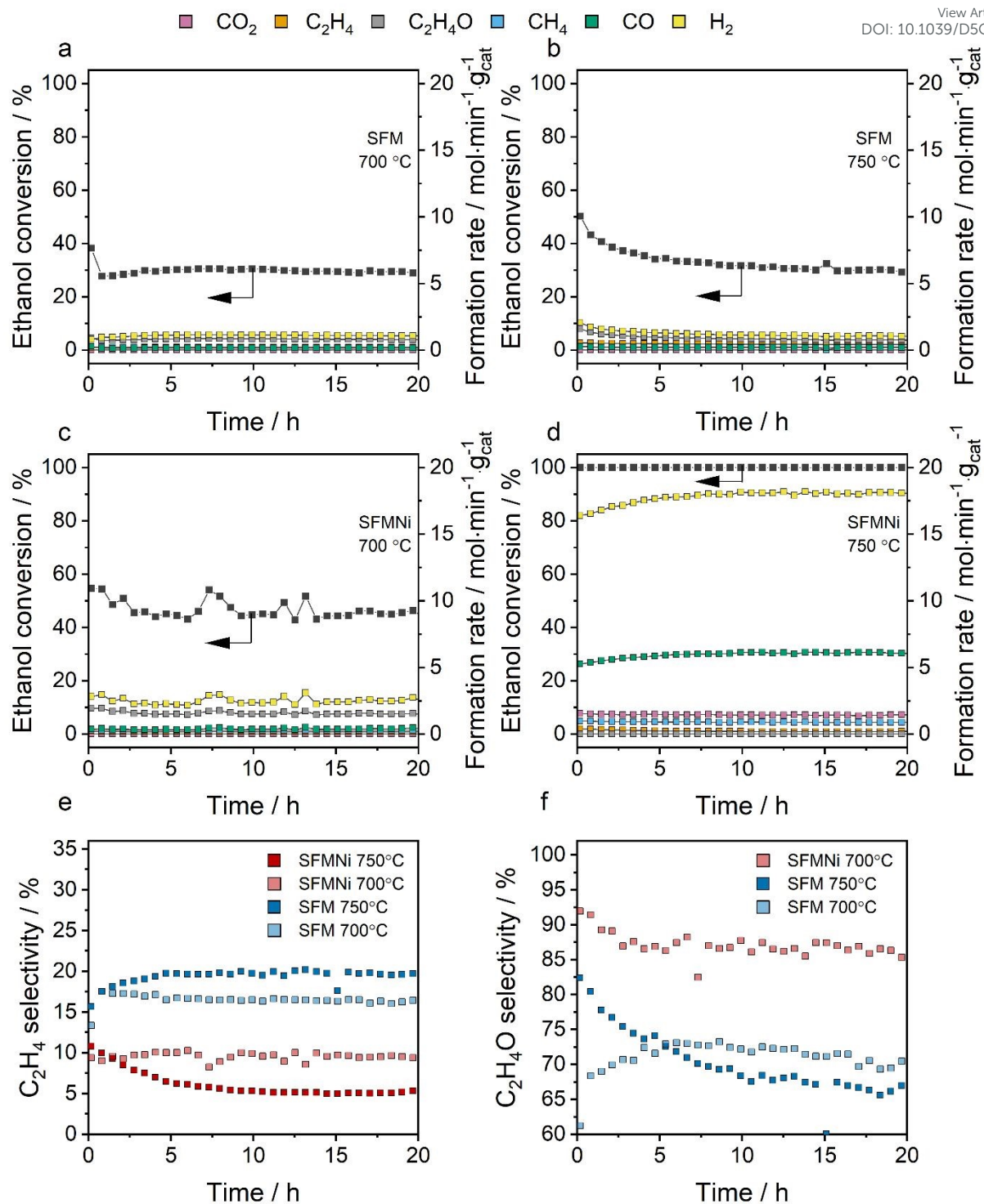


Figure 3. Ethanol conversion, product formation rates and selectivity during ESR (2.6% EtOH-10.4% H₂O-N₂). (a) SFM at 700 °C, (b) SFM at 750 °C, (c) SFMNi at 700 °C, and (d) SFMNi at 750 °C, illustrating the influence of temperature and Ni incorporation on ethanol conversion and the generation of reforming products. Influence of catalyst and temperature on (e) ethylene (C₂H₄) and (f) acetaldehyde (C₂H₄O) selectivity, indicating effect of surface acidity on dehydration and dehydrogenation reaction pathway with SFMNi at 750 °C lacking C₂H₄O selectivity due to complete acetaldehyde steam reforming.



At 750 °C, SFMNi exhibits significantly enhanced ESR activity, achieving complete ethanol conversion over the course of 20 h (**Figure 3**). During the initial reaction hours, H₂ and CO production increase and stabilize at 18.1 and 6.1 mol·min⁻¹·g_{cat}⁻¹, respectively, indicating that ESR is the dominant pathway. During the 20 h experiment, only minor traces of ethylene were detected, while acetaldehyde was completely absent. This suggests that the sites enable efficient C-C bond cleavage of ethylene and acetaldehyde to produce H₂ and CO. The low CO₂ formation indicates a negligible contribution from the water-gas shift reaction, consistent with its exothermic nature being thermodynamically disfavored at elevated temperatures. This reveals an untapped potential for additional hydrogen formation, which could be enabled by further tailoring the surface chemistry for CO adsorption and steam dissociation.⁴²

The relative differences in ethylene and acetaldehyde selectivity between SFM and SFMNi are consistent with NH₃-TPD and CO₂-TPD measurements, which reveal a higher affinity of SFM for ethanol dehydration to ethylene, whereas SFMNi favors ethanol dehydrogenation (**Figure 3e,f**). These results demonstrate that Ni doping modifies the surface acidity, enhancing selectivity toward acetaldehyde formation while suppressing ethylene, a known coke precursor through oligomerization.³⁷

Post-testing characterization

The combined effect of high temperature, Ni doping and the reducing environment induced by ethanol reforming may drive *operando* exsolution of metallic nanoparticles facilitating efficient ESR performance. This mechanism is investigated by post-mortem XRD data (**Figure 4a,b**), revealing a discrete peak at ~44° assigned to the FeNi₃ alloy phase after ESR at 750 °C for 20 h. HAADF-STEM characterisation combined with elemental mapping corroborates the presence of Ni-Fe alloy nanoparticles on the surface of SFMNi after ESR at 750 °C for 20 h (**Figure S3**). STEM-EDX quantification of three selected areas reveals a clear difference from the total mapped area (**Figure S5**). All selected areas show reduced atomic fractions of O, Sr, and Mo relative to the bulk composition, accompanied by pronounced Ni enrichment (**Table S1**). A slight Fe enrichment is also observed in most regions, suggesting segregation of Fe with Ni supporting the presence of the FeNi₃ alloy phase.

The characteristic at ~44° peak is however absent in the diffraction pattern of spent SFMNi at 700 °C, indicating that the conditions were insufficient to induce exsolution, either due to the weak reducing environment from limited ethanol dehydrogenation or the lower thermal driving force. However, lowering the temperature has been shown to generate exsolved particle size distributions advantageous for high catalytic performance.⁴³ Regardless of temperature, SFMNi exhibited excellent structural integrity, as evidenced by the absence of secondary peaks in the diffraction patterns. The diffraction patterns of spent SFM after ESR testing at 700 and 750 °C confirm excellent structural stability, with no detectable secondary reflections. Moreover, no reflections attributable to metallic phases were observed, indicating the absence of the key component for enhanced ESR performance.



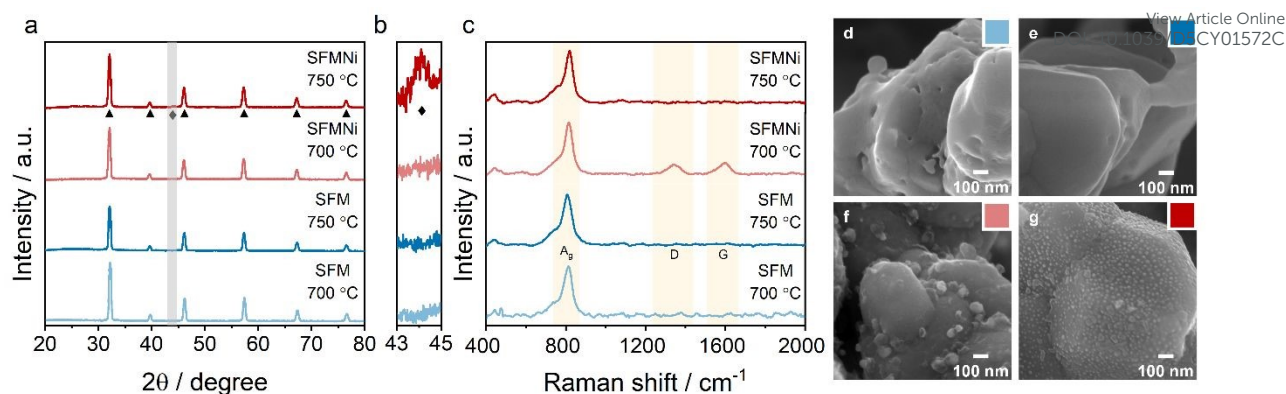


Figure 4. Post-test crystallographic and spectroscopic characterization of spent SFM and SFMNi after ethanol-steam reforming (2.6% EtOH-10.4% H₂O-N₂) at 700 and 750 °C for 20 h. **(a)** XRD patterns demonstrating structural integrity of the spent powders, **(b)** magnified region (43-45°) highlighting the peak at 44°, indicative of Ni-Fe nanoparticle formation, **(c)** Raman spectra evidencing the presence or absence of carbon deposition on the spent catalyst powders and SEM imaging illustrating morphological change of **(d)** SFM 700°C, **(e)** SFM 750°C, **(f)** SFMNi 700°C and **(g)** SFMNi 750°C.

Post-test characterization by Raman spectroscopy and SEM reveals correlated structural and morphological changes that reflect carbon tolerance and activity (**Figure 4c-f**). All samples display characteristic double-perovskite modes, with a high-frequency peak near 800 cm⁻¹ assigned to A_g stretching vibrations and a low-frequency peak near 750 cm⁻¹ corresponding to B_g anti-stretching/bending modes.⁴⁴ SFM shows no carbon-related bands or morphological changes at either temperature, consistent with its negligible reforming activity (**Figure 4d,e**). For SFMNi at 700 °C, Raman spectra show carbon-related D (~1350 cm⁻¹) and G (~1590 cm⁻¹) bands,⁴⁵ consistent with SEM evidence of surface carbon deposits (**Figure 4f**),⁴⁶ indicating partial deactivation. SEM imaging reveals the presence of exsolved particles on SFMNi at 700 °C (**Figure 4f**), while a distinct crystallographic signature of exsolution is not observed. This is further corroborated by back-scattered electron imaging, which provides clear Z-contrast differentiation between the support, the exsolved phase, and carbonaceous species (**Figure S2**). Carbon formation appears to proceed via a characteristic base-growth mechanism on the exsolved nanoparticles, driven by strong metal-support interactions, rather than through the tip-growth mechanism commonly observed on deposited nanoparticles.²⁴ Although desorption measurements (**Figure 1**) and thermocatalytic evaluation (**Figure 3**) indicate higher ethanol dehydration selectivity on SFM than on SFMNi, coking observed on SFMNi suggests either the presence of an alternative coking mechanism or an increased availability of coke precursors (acetaldehyde + ethylene) due to its higher reforming activity. Nevertheless, at 750 °C, SFMNi lacks these carbon bands, instead displaying pronounced exsolved nanoparticles in SEM images (**Figure 4g**), in agreement with its sustained catalytic performance.



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Electrochemical tests of SFM and SFMNi fuel electrode materials were conducted to evaluate the influence of exsolved Ni–Fe nanoparticles on direct ethanol SOFC using a 2.6% EtOH-10.4% H₂O-N₂ fuel inlet at 750 °C (**Figure 5**). The electrolyte-supported cell architecture (SFM(Ni)-GDC/GDC//ScSZ//GDC/LSCF-GDC/LSCF) is shown in **Figure S5**. A GDC barrier layer was introduced to enhance electrode-electrolyte adhesion and suppress SrZrO₃ formation at the interface.⁴⁷ To further improve oxygen-ion conductivity, the fuel electrodes were prepared as SFM- and SFMNi-GDC composites (see Experimental Section).⁴⁸ Cross-sectional SEM analysis of the sintered fuel cell confirmed uniform deposition of functional layers on the ScSZ electrolyte (~153 μm thick). A dense GDC barrier layer (~5 μm) was observed at both fuel and air interfaces, confirming strong adhesion after high-temperature sintering (**Figure S5c,d**). The SFMNi-GDC, LSCF-GDC and LSCF electrode layers exhibited homogeneous, highly porous microstructures with a thickness of ~12.6, 9.9 and 8.0 μm, respectively, favoring gas transport to and from the electrochemically active region. It should be noted that GDC exhibits good electrochemical performance when used as a pure anode. However, previous studies have reported that composite SFMNi-GDC electrodes outperform GDC alone.⁴⁹

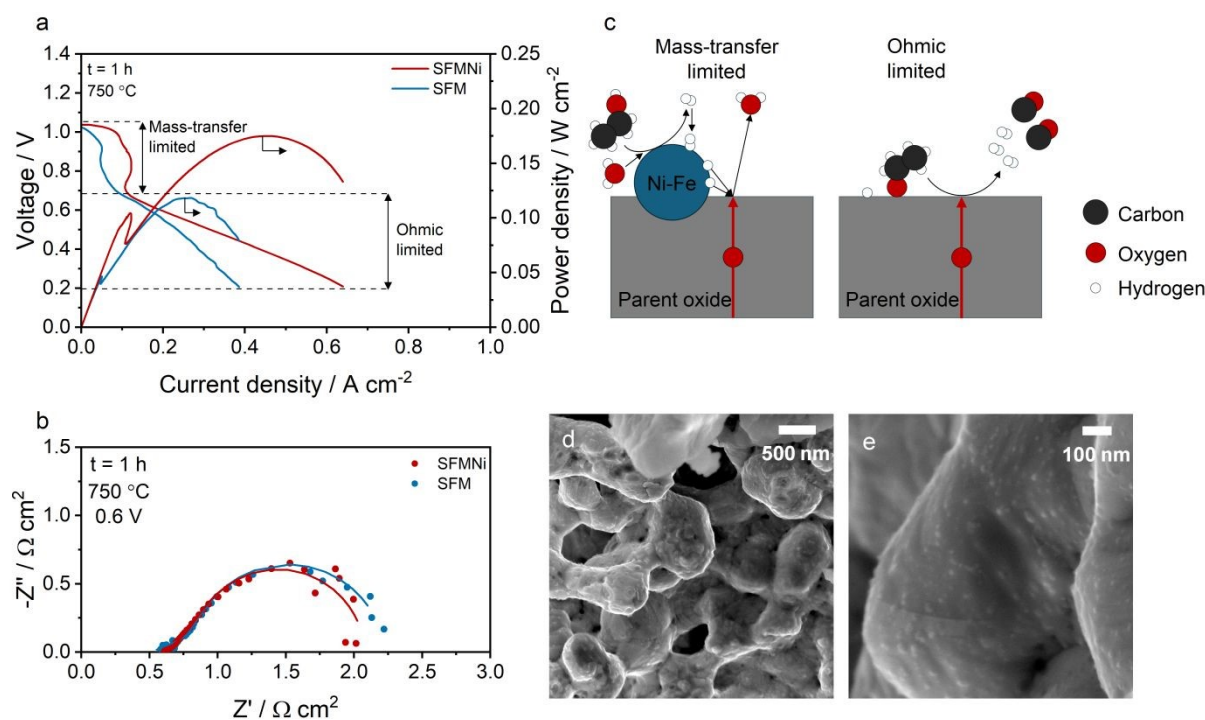


Figure 5. SOFC performance of SFM and SFMNi fuel electrodes in an ethanol-steam atmosphere (2.6% EtOH-10.4% H₂O-N₂) at 750 °C. **(a)** current-voltage and power density curves after 1 h on stream, highlighting enhanced indirect SOFC operation and increased power output due to internal reforming over exsolved Ni-Fe nanoparticles, **(b)** Nyquist plots recorded at 0.6 V after 1 h, illustrating resistance contributions of both cells, **(c)** schematic representation of the role of exsolved Ni-Fe nanoparticles in promoting internal reforming and indirect ethanol utilization and **(d-e)** SEM imaging on SFMNi fuel electrode evidencing presence of exsolved nanoparticles during ethanol fueled SOFC operation.



The electrochemical performance was evaluated by current voltage curves from OCV to 0.2 V and impedance spectroscopy diagrams at 0.6 V at two different time intervals at $t = 0$ (**Figure S6**) and $t = 1$ h (**Figure 5**). The current-voltage (**Figure 5a**) curve shows two distinct regimes: mass-transfer limited region (from OCV to ~ 0.7 V) and a ohmic limited region (~ 0.7 to 0.2 V) controlled by charge transfer and ohmic losses. In the mass-transfer limited regime (**Figure 5a**), the current is sustained by the oxidation of hydrogen from ESR, with the voltage decline in this range reflecting a mass transfer-limited regime due to hydrogen consumption and depletion. Below 0.7 V, the system transitions to an ohmic limited region, where energetics become favorable to directly oxidize ethanol and kinetics are dominated by charge transfer rather than mass transport, delivering peak power densities of 0.118 and 0.161 mW cm⁻² for SFM and SFMNi respectively (**Figure S6**). It should be noted, however, that intermediate products such as acetaldehyde and ethylene may also be oxidized within this region.

The mass transfer-limited region in ethanol SOFCs has been attributed to hydrogen produced by the ESR thermocatalytic conversion of ethanol to hydrogen at the anode surface.^{13, 14} Enhancing thermocatalytic activity, either by increasing temperature or by functionalizing the perovskite surface, is therefore expected to increase hydrogen availability and improve electrochemical performance. While SFM does not undergo surface functionalization via redox exsolution (**Figure 4a**), SFMNi has been shown to exsolve Ni-Fe nanoparticles *operando* under ethanol-steam mixtures (2.6% EtOH-10.4% H₂O-N₂). Such feature is further confirmed by SEM imaging of an identical cell with a SFMNi fuel electrode aged in 2.6% EtOH-10.4% H₂O-N₂ for 2 h at 750 °C evidences the presence of nanoparticles on the surface (**Figure 5d,e**). The (**Figure 5a**) current-voltage measurements at $t = 1$ h revealed a significant change in the mass-transfer limited region for SFM and SFMNi relative to the current-voltage measurement at $t = 0$ (**Figure S6**). **Figure S7** shows that the voltage limitation below ~ 0.7 V in 2.6% EtOH-10.4% H₂O-N₂ is due to limited H₂ availability, as this limitation is not observed under 97% H₂-H₂O. For the SFMNi with increased ESR performance the hydrogen production was enhanced and fuel cell performance at low current was significantly extended, accompanied by a local power density peak of 0.104 mW cm⁻² at 0.86 V. Further increasing current density, in the ohmic limited region, the peak power densities for SFM and SFMNi were 0.118 and 0.175 mW cm⁻², respectively. Nonetheless, SFMNi exhibits a significant enhancement of as compared to SFM with a considerable larger limiting current. The Nyquist plot at 0.6 V (**Figure 5c**) reveals that the performance difference between SFM and SFMNi is primarily attributed to polarization resistance, $R_p = 1.74$ and 1.50 Ohm·cm², respectively, rather than ohmic resistance $R_0 = 0.52$ and 0.61 Ohm·cm², respectively. This is evidenced by similar first intercepts with the real axis, while the reduced second intercept for SFMNi reflecting its lower R_p . Equivalent circuit fitting parameters are summarized in **Table S2** (Supplementary Information). Deconvolution of R_p into two constant phase elements shows that the largest variation arises from the low-frequency resistance (R_2), corresponding to gas adsorption and surface diffusion processes.⁵⁰⁻⁵² This contribution is reduced in SFMNi, consistent with the



functionalization by exsolved Ni-Fe nanoparticles. Such nanoparticles may enhance H₂ adsorption, as supported by DFT calculations indicating more favorable energetics on Ni(111) and Fe(110) surfaces compared to SFM(001).⁵³⁻⁵⁵

These findings highlight the potential of nanoparticle-functionalized perovskite electrodes for alcohol (or hydrocarbon) -fueled SOFC systems, as schematically illustrated in **Figure 4c**. Enhanced reforming activity increases hydrogen partial pressure, thereby indirectly improving electrochemical performance. Although steam reforming is an endothermic process, the required energy can be supplied by heat, enabling efficient electricity generation at the expense of thermal energy while simultaneously achieving higher power densities and facilitating more compact, lightweight SOFC designs.

Long-term stability evaluation

The long-term stability of the SFMNi cell was evaluated at a constant voltage of 0.6 V over 168 hours (**Figure 5**). The initial current density of 0.254 A cm⁻² gradually decreased to 0.208 A cm⁻², primarily during the first 70 hours after which the cell stabilized reaching 0.212 A cm⁻² at 168 h. Nyquist plots recorded at 0.6 V at different time intervals (t = 1, 70, and 168 h) reveal that the long-term degradation predominantly arises from processes in the mid- to low-frequency range (<10 Hz), while the stable first intercept with the real axis confirms an unchanged ohmic contribution of the cell (**Table S2**). This indicates that the degradation is not associated with the electrolyte, or contact resistance in the electrolyte/electrode interface, confirming the robustness of the cell architecture and fabrication of the electrolyte-supported cell. Similarly, the dominant variation in R_p originates from the low-frequency resistance (R₂), associated with gas adsorption and surface diffusion, suggesting that the fuel electrode suffers from carbon deposition, particle coarsening or sintering of the grain boundaries.⁵⁶ Raman analysis of the spent cell after 168 h on stream confirms carbon deposition through the appearance of the D-band (~1350 cm⁻¹) and G-band (~1590 cm⁻¹). Nevertheless, the stable current density after 70 h on stream indicates that carbon formation on the electrode surface reaches a steady state.

Conclusions

In this study we have demonstrated that *operando* exsolved FeNi₃ nanoparticles on SFM-based fuel electrodes are crucial for boosting the performance of ethanol-fueled SOFCs. Doping Ni in SFM (SFMNi) increased surface basicity and oxygen vacancy concentration, thus shifting ethanol steam reforming selectivity toward dehydrogenation compared to SFM. Thermocatalytic experiments revealed that SFMNi exhibits superior ethanol steam reforming activity at 750 °C compared to the undoped SFM sample. The crystallographic and Raman analyses revealed the presence of exsolved FeNi₃ nanoparticles on SFMNi which are highly tolerant to coking. The electrocatalytic evaluation of the samples as fuel electrodes at 750 °C demonstrate that exsolved FeNi₃ nanoparticles on the SFMNi fuel electrode enabled double the power densities than the SFM electrode due to the higher hydrogen



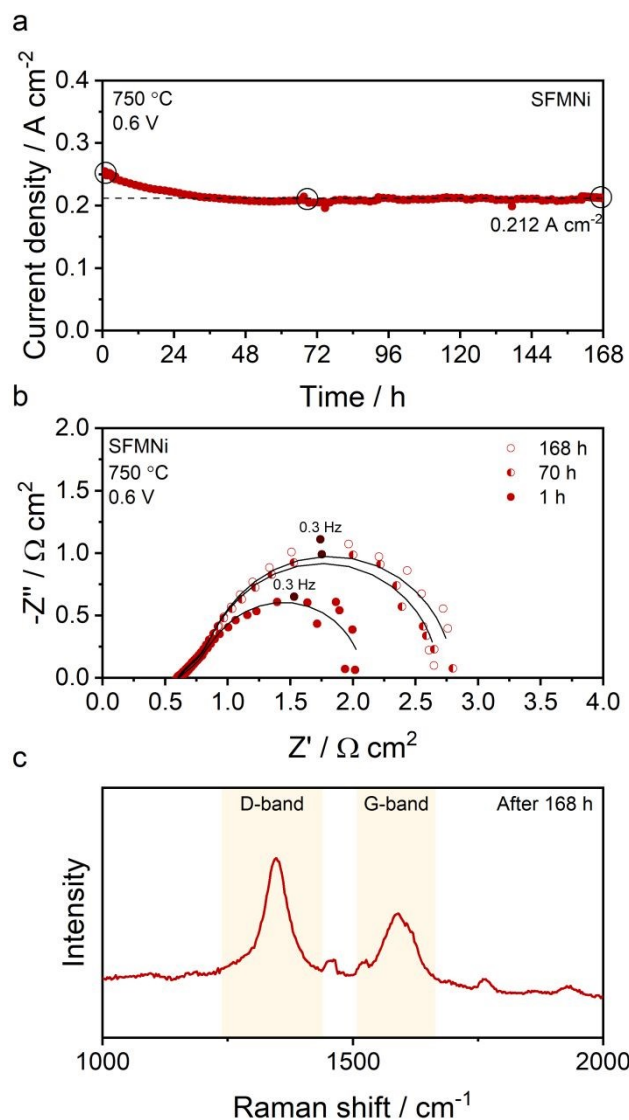


Figure 6. Long-term stability of the SFMNi fuel electrode in an ethanol-steam atmosphere (2.6% EtOH-10.4% H₂O-N₂) at 0.6 V and 750 °C. **(a)** Potentiostatic performance at 0.6 V over 7 days, **(b)** corresponding Nyquist plots recorded after 1 h, 70 h, and 168 h, illustrating the evolution and stability of cell resistance contributions and **(c)** Raman spectroscopy of the spent cell after 168 h demonstrating the presence of carbon deposits.

formation rates through ethanol steam reforming. The optimum electrolyte-supported cell with SFMNi fuel electrode showed considerably stable operation after 168 h (1 week) at 0.212 A cm⁻² after some hours of stabilisation. These findings exemplify the importance of designing nanoengineered MIEC electrodes with the suitable catalytic properties through operando exsolution towards enhancing the performance and stability of bioethanol-fueled SOFCs.



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Data availability statement

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The authors confirm that the data supporting the findings in this study are available within the article and included as part of the supplementary information (SI).

