

# Electrochemical evaluation of nickel oxide addition toward lanthanum strontium cobalt ferrite cathode for intermediate temperature solid oxide fuel cell (IT-SOFCs)

Ahmad Fuzamy Mohd Abd Fatah <sup>1</sup>, Ahmad Zaki Rosli <sup>1</sup>, Ahmad Azmin Mohamad <sup>2</sup>, S.A. Muhammed Ali <sup>3</sup>, Andanastuti Muchtar <sup>3</sup> and N. A. Hamid <sup>1, \*</sup>

<sup>1</sup> School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal Penang, Malaysia

<sup>2</sup> School of Materials & Mineral Resources, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal Penang, Malaysia

<sup>3</sup> Fuel Cell Institute, Universiti Kebangsaan Malaysia, UKM, 43600 Bangi, Selangor, Malaysia

\* Correspondence: chrina@usm.my

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**Abstract:** A mixture of lanthanum strontium cobalt ferrite (LSCF) and nickel oxide (NiO) is a desirable cathode material for an IT-SOFC due to excellent oxygen reduction capability. This study investigates the effect of NiO addition into LSCF cathode on its physical and electrochemical properties. To optimise the amount of NiO addition, electrochemical impedance spectra and bode phase were used to examine various weight ratios of nickel oxide and LSCF cathode. Brunauer-Emmett-Teller (BET) and thermal analyses validated the electrochemical observation that the LSCF:NiO ratio yields sensible oxygen reduction reaction and stoichiometric findings. Initial characterisation, comprising of phase and bonding analyses, indicated that LSCF-NiO was successfully synthesised at 800 °C using an improved modified sol gel technique. The addition of 5% nickel oxide to LSCF results in the lowest area specific resistance (ASR) value overall. The Bode phase implies that the addition of 5% nickel oxide to LSCF reduces the impedance at low frequencies by 64.28 percent, indicating that a greater oxygen reduction process happened at the cathode. After the addition of 5 wt% NiO, a single LSCF-NiO cell may function at temperatures as low as 650 °C and the LSCF cathode power density is increased by 25.35%. The surface morphology of the LSCF-NiO cathode reveals that the average particle size is less than 100 nm, and mapping analysis demonstrated a homogenous NiO distribution over the cathode layer. Consequently, the synthesis of LSCF-NiO at intermediate temperatures (800 – 600 °C) revealed outstanding chemical compatibility, bonding characteristics, and electrochemical performance.

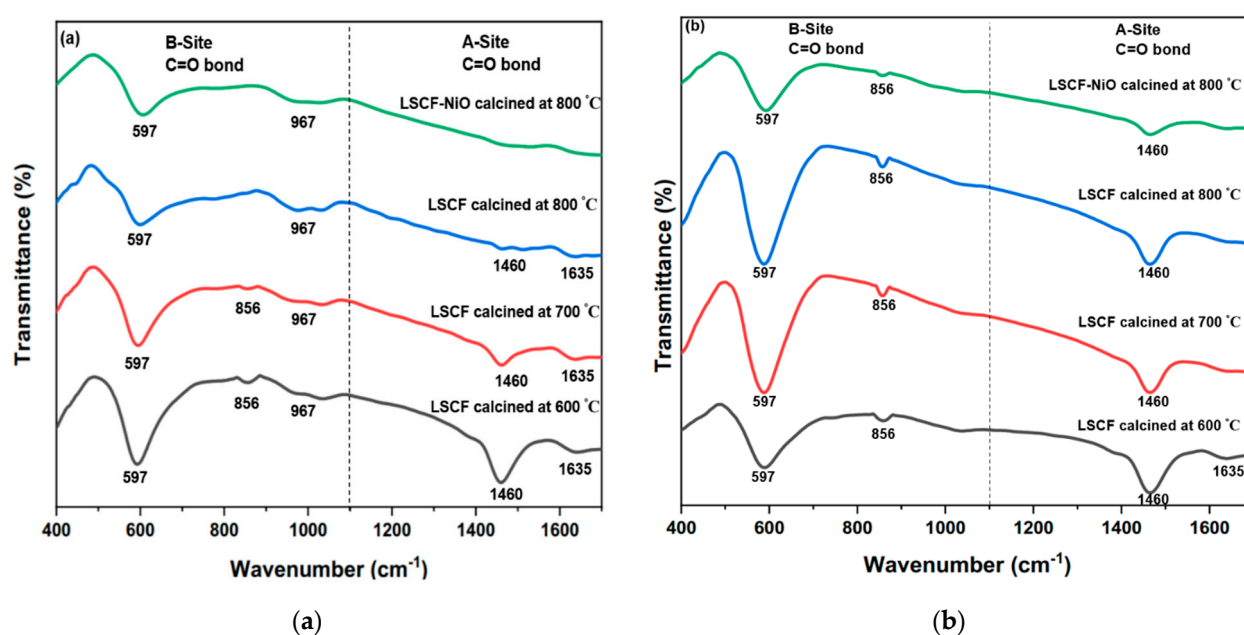
**Keywords:** solid oxide fuel cell; oxygen reduction reaction in cathode; optimization of LSCF and nickel oxide ratio as cathode material.

## 1. Supporting Information

Further elaboration on carbonate existence was revealed via phase analysis towards LSCF-NiO for both methods (EM-SG and Pechini method). The experiment was carried out with bare LSCF and LSCF-NiO calcined at 600 °C, 700 °C, and 800 °C, respectively. According to **Figure S1a**, there are three visible peaks that occurred at 967, 1460, and 1635 cm<sup>-1</sup> for each respective sample, and these peaks were categorized as carbonate bonds that exist in two sections, namely A-site and B-site. The band between 600 and 1100 cm<sup>-1</sup> is categorized as the vibration mode of carbonate ions, while the band between 1400 and 1700 cm<sup>-1</sup> is described as the symmetrical and asymmetrical stretching mode of carbonate bonds, which in this case is attributed to the creation of SrCO<sub>3</sub> [1–3].

It was observed that increasing the calcination temperature up to 800 °C caused the carbonate bond to disappear. The peak intensity on B-site shows a minor reduction, while the peak on A-site gradually disappears as the temperature increases. Small intensity, classified as carbonate trace intensity, also indicated that the sample had appropriate calcination temperature, contributing to a high purity sample in which the carbon was virtually eliminated [4]. Therefore, low carbonate bond exists in the A-site structure ( $\text{La}^{3+}$  and  $\text{Sr}^{3+}$ ) in LSCF perovskite indicates that a complete perovskite structure has formed at that calcination temperature, which in this case is at 800 °C where minor peak intensity is detected at 1460  $\text{cm}^{-1}$  and 1635  $\text{cm}^{-1}$ , which can be depicted as a trace of carbonate bond. The addition of NiO towards LSCF also shows a minor change in peak intensity for both sites (A-site and B-site), which indicates the addition of NiO did not alter the phase that occurred in the LSCF structure, thus agreeing with bonding analysis that stated NiO has good chemical compatibility with LSCF.

Compared with phase analysis depicted in **Figure S1b**, the sample shows a visible peak at A-site of bare LSCF and LSCF-NiO that was calcined at 800 °C, indicating a higher calcination temperature is required for complete LSCF perovskite. It is critical to maintain a low carbonate level because carbon deposition during ion exchange can plug the pores, reducing electrochemical performance since porous structures can offer rapid ionic channels for ionic transport [4, 5]. Further electrochemical analysis toward LSCF-NiO can only be conducted toward LSCF-NiO synthesized via the EM-SG method, as the EM-SG method shows much more promising results than the Pechini method.



**Figure S1.** FTIR spectra of LSCF powder synthesised via (a) EM-SG method and calcined at 600 °C, 700 °C and 800 °C, LSCF with 5 wt% of NiO powder calcined at 800 °C. (b) Pechini method and calcined at 600 °C, 700 °C and 800 °C, LSCF with 5 wt% of NiO powder calcined at 800 °C

In section 3.2, the optimization was done via electrochemical analysis and supported by specific surface area. At operation temperature 800 °C, the ASR of bare LSCF was reduced from 0.09  $\Omega \text{ cm}^2$  to 0.06  $\Omega \text{ cm}^2$  after further addition of nickel oxide up to 7 wt% revealed an increase of ASR up to 0.11  $\Omega \text{ cm}^2$  while it continuously increases to 0.16  $\Omega \text{ cm}^2$  when the nickel oxide content reaches 9 wt%. These findings are coherent with specific surface area from BET as shown in manuscript. Further electrochemical analysis on different operating temperature also suggests LSCF + 5wt% of NiO is a sensible choice as the overall ASR value was lower than bare LSCF. The data table was included below and will be inserted in supporting information. To explain the degradation ASR occurred at LSCF with 7 wt% and 9 wt%

of NiO, it could be summarized as the abundance of NiO particle presence in the LSCF cathode structure that blocked LSCF pores. The ORR process will be hampered, raising the ASR value. In addition, it was said that optimum cathode porosity should be between 40% and 20% for the ORR process to take place [6, 7]. As a result, adding nickel oxide above 7% may potentially inhibit the ORR process due to pore obstruction caused by an excess of nickel oxide particles.

**Table S1.** ASR tabulated data for LSCF with different NiO loading at different operating temperature

Area specific resistance (m <sup>2</sup> /g)	Operating temperature				
	800 °C	750 °C	700 °C	650 °C	600 °C
LSCF	0.09	0.28	0.58	1.50	3.96
LSCF + 5wt% NiO	0.06	0.11	0.24	0.55	1.44
LSCF + 7wt% NiO	0.11	0.14	0.34	0.85	2.35
LSCF + 9wt% NiO	0.16	0.29	0.64	1.64	4.71

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