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N- and S-doped mesoporous carbon as metal-free cathode catalysts for direct biorenewable alcohol fuel cells

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Abstract
Nitrogen and sulfur were simultaneously doped into the framework of mesoporous CMK-3 as metal-free catalysts for direct biorenewable alcohol fuel cells. Glucose, NH3, and thiophene were used as carbon, nitrogen and sulfur precursors, respectively, to prepare mesoporous N-S-CMK-3 with uniform mesopores and extra macropores, resulting in good O2 diffusion both in half cell and alcohol fuel cell investigations. Among all investigated CMK-3 based catalysts, N-S-CMK-3 prepared at 800 °C exhibited the highest ORR activity with the onset potential of 0.92 V vs. RHE, Tafel slope of 68 mV dec−1, and 3.96 electron transfer number per oxygen molecule in 0.1 M KOH. The alkaline membrane-based direct alcohol fuel cell (DAFC) with N-S-CMK-3 cathode displayed 88.2 mW cm−2 peak power density without obvious O2 diffusion issue, reaching 84% initial performance of that with a Pt/C cathode. The high catalyst durability and fuel-crossover tolerance led to stable performance of the N-S-CMK-3 cathode DAFC with 90.6 mW cm−2 peak power density after 2 h operation, while the Pt/C cathode-based DAFC lost 36.9% of its peak power density. The high ORR activity of N-S-CMK-3 can be attributed to the synergistic effect between graphitic-N and S (C–S–C structure), suggesting great potential to use N-S-CMK-3 as an alternative to noble metal catalysts in the fuel cell cathode.

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Full Papers

N- and S- Doped Mesoporous Carbon as Metal-Free Cathode Catalysts for Direct Biorenewable Alcohol Fuel Cells

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Nitrogen and sulfur were simultaneously doped into the framework of mesoporous CMK-3 as metal-free catalysts for direct biorenewable alcohol fuel cells. Glucose, NH3, and thiophene were used as carbon, nitrogen and sulfur precursors, respectively, to prepare mesoporous N,S-CMK-3 with uniform mesopores and extra macropores, resulting in good O2 diffusion both in half cell and alcohol fuel cell investigations. Among all investigated CMK-3 based catalysts, N,S-CMK-3 with a 800 °C doping temperature exhibited the highest ORR (close to that of Pt/C) activity with 4.0 electron/oxygen molecule and kinetic-limiting current density (Jk) of 32.6 mA cm−2 at 0.5V (vs RHE) in 0.1M KOH. The alkaline membrane-based direct alcohol fuel cell (DAFC) with N,S-CMK-3 cathode displayed 88.2 mW cm−2 peak power density without obvious O2 diffusion issue, reaching 84% initial performance of that with a Pt/C cathode. The high catalyst durability and fuel-crossover tolerance led to stable performance of the N,S-CMK-3 cathode DAFC with 90.6 mW cm−2 peak power density after 2-hour operation, while the Pt/C cathode-based DAFC lost 36.9% of its peak power density. The high ORR activity of N,S-CMK-3 can be attributed to the synergistic effect between graphitic-N and S (C-S-C structure), suggesting great potential to use N,S-CMK-3 as an alternative to noble metal catalysts in the fuel cell cathode.

1 Introduction

With increasing energy demands, declining petroleum reserves and increasing environmental pressure, having clean, sustainable, reliable and technical viable energy resources is one of the most significant challenges facing human society, industry and the economy.1,2 Sustainable energy conversion and storage technologies, such as fuel cells, metal-air batteries, etc., attract enormous attention and have been intensively studied and developed given their potential for high energy-conversion efficiency and environmental advantages.3 6 However, the sluggish oxygen reduction reaction (ORR), one of the half electrochemical reactions occurring at the cathode side, results in significant overpotential even at open circuit voltage operation (>250 mV), and largely limits the fuel cell’s working efficiency and output power density.6 7 The noble metal-based catalysts, e.g. Pt, have been found to be the best ORR catalysts at low temperatures, but they suffer from several serious issues including their limited reserves on the earth, high cost and instability under the fuel cell operation environment.4 7 For direct alcohol fuel cells, noble metal-based ORR catalysts further have an alcohol poisoning issue, which is originated from the crossover of alcohol fuel from the anode to cathode.6 8 With the alcohol crossover, electrochemical oxidation of alcohol competes with the ORR at the cathode and results in a mixing potential, thus reducing the fuel cell operating voltage and efficiency. Therefore, there is a clear and urgent need to seek for alternative noble metal-free or even metal-free cathode catalysts with high ORR activity, low economic cost, robust stability and high tolerance towards alcohol fuels.

One strategy is to lower the noble metal content in the ORR catalysts. Adzic and co-workers reported the underpotential deposition method to fabricate a Pt monolayer on Au and Co.9 10 MPt (M=Fe, Co etc.) alloys and core-shell (noble metal core) catalysts were also investigated to reduce the noble metal content.8 11 Another strategy is to replace Pt by transition metal macrocycle catalysts prepared through pyrolysis processes. Although these catalysts demonstrated competitive ORR activity relative to Pt, they suffer significant activity loss due to instability of the transition metal in the acid electrolyte.12 Recently, nitrogen doped carbon has been discovered as a metal-free ORR catalyst in a high pH medium. For example, metal-free nitrogen-doped carbon nanotubes were shown to have remarkable ORR activity and durability.13 It has been reported that the carbon materials could become non-electron-neutral by incorporating N atoms into the graphitic framework. The electronic property tuning effect of N atoms can significantly change the charge density and spin density of carbon atoms; thus benefiting the adsorption of oxygen and subsequent reduction reaction on carbon.13 14 Besides nitrogen, other elements, such as S, B and P, etc., can

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also be incorporated into the carbon framework as a dopant or co-dopant with N to further enhance the ORR activity based on the synergistic effects between the two dopants.15–19 Unfortunately, some undesired structures/phases (e.g. boron nitride, BN) could be formed under high temperature annealing conditions, and can significantly lower the ORR activity of the catalysts.14,20 Thus, rational choice of dual-dopants and its corresponding precursors play an important role in obtaining high ORR activity. However, few reports explain the criterion for choosing heteroatom precursors or investigate the precursor effect on ORR activity over heteroatom-doped nanocarbons.

Among nanocarbon materials, heteroatom-doped carbon nanotubes and graphene, one or two dimensional carbon networks with outstanding electric conductivity, have demonstrated excellent ORR performance, and have emerged as promising ORR catalyst candidates.21–23 However, their relatively low electrochemical surface area (ECSA) and randomly formed oxygen-inaccessible micropores may lead to internal diffusion issues in practical single fuel cell cathode applications.6,24 In comparison, mesoporous carbon nanostructures are more advantageous to serve as the cathode catalyst in a real fuel cell setting, because they feature not only high conductivity, but also well-ordered pore structure and tunable uniform mesopores (e.g. 4-20 nm) with a high ECSA (≥1000 m² g⁻¹).25–27 Heteroatom (e.g. N) containing hydrocarbons are potentially attractive to serve as the carbon precursor; but some of them are very expensive with price even comparable to noble metals.28–30 Thus, carbon precursor cost should also be taken into consideration for the catalyst preparation and utilization in fuel cells.

Heteroatom-doped carbons are rarely directly employed as cathode catalysts in H₂/O₂ fuel cell, which is probably due to the membrane-electrode-assembly (MEA) fabrication issues,7,31 underperforming the electricity generation of H₂/O₂ fuel cells. For low temperature fuel cells directly fed with biomass-derived alcohols, such as ethanol and polyols, they are also attractive because they do not need a fuel reforming system and rigorous MEA fabrication process.32,33 In addition, the direct biorenewable alcohol fuel cells can simultaneously convert chemical energy into electrical energy and co-produce desirable biobased chemicals with the advantages of high efficiency, quiet operation and low CO₂ emission.34 Therefore, they are poised to take a significant role in our future energy landscape. US DOE has identified the top ten important chemicals, including ethanol, polyols (glycerol, sorbitol, etc.),34 which can be economically derived from biomass, and can serve as building blocks for chemicals, fuels and energy production in the future.

Herein, we report a nitrogen and sulfur dual-doped, metal-free mesoporous carbon (N-S-CMK-3) with outstanding electrocatalytic activity for ORR and its utilization as a cathodic catalyst in a direct biorenewable alcohol fuel cell, which exhibits remarkable performance and operation stability as compared with a noble metal Pt/C cathode fuel cell. A ubiquitous environment-friendly renewable biomass compound, glucose, serves as the carbon sources. Highly active N and S are introduced from ammonia (NH₃) and thiophene precursors, which can efficiently prevent N-S-CMK-3 from having clogged inside pores and channels thereby obtaining a highly organized mesoporous structure with high surface area. Simultaneously generating macropores (pore diameter > 200 nm) together with mesopores improves the adsorption of O₂ and increases the electrocatalytic activity for ORR. After ruling out the transition metal (Fe) effect, high ORR activity and fuel cell performance can be largely ascribed to the synergistic effect of N and S atoms with specific structures (e.g. graphitic-N and C-S-C). The high ORR activity of N-S-CMK-3 with robust stability and excellent tolerance of alcohol crossover in the direct alcohol alkaline fuel cell is superior to that of noble metals and holds promise of serving as cathode catalyst for other energy conversion and storage devices, such as the H₂/O₂ fuel cells and metal-air batteries.

2 Experimental

2.1 Material Preparation

The synthesis of CMK-3 uses SBA-15 as the template. For the synthesis of SBA-15,35 Pluronic P123 (5.0 g) was dissolved in a hydrochloric solution (190 mL, 1.6 M) with 350 rpm stirring at 35 °C. After the dissolution of P123, tetraethyl orthosilicate (11.0 g) was added into the solution and stirred at 35 °C for another 24 h. The solution was then moved into a polytetrafluoroethylene bottle for an additional 24 h treatment at 100 °C. After that, the solid was filtered and washed with deionized water (18.2 MQ) and dried in an oven overnight. A final calcination in air at 550 °C for 6 h was used to remove the surfactant. Then, SBA15 (2.8 g) was mixed with deionized water (15 g), glucose (3.5 g), and sulfuric acid (0.39 g). The mixture was treated at 100 °C for 6 hours, and then at 160°C for another 6 hours. Deionized water (15 g), glucose (2.24 g), and sulfuric acid (0.25 g) was again added, mixed, and treated under the same condition described above. The sample was then heated at 900 °C and kept for 10 h under flowing nitrogen. The sample was treated with 10% hydrofluoric acid in ethanol solution (50% by volume) to remove silica. After filtration and drying, the base CMK-3 was obtained.

The nitrogen and sulfur dual-doped N-S-CMK-3 catalysts were synthesized under high temperature annealing. 0.5 g thiophene and 0.5 g iron chloride (FeCl₃) were dissolved into 15 ml of ethanol with magnetic stirring, followed by directly adding 0.5 g CMK-3, and the mixture was left under magnetic stirring at ambient temperature for 12 h. The pre-treated CMK-3 was obtained by filtering and washing with deionized water for 5 times to remove iron chloride residue followed by drying at 80 °C for 12 h. After completely removing the liquid solution, the pre-treated CMK-3 was annealed in ambient pressure NH₃ gas with a 60 ml min⁻¹ flow rate. The temperature was kept at 700, 800 and 900 °C for 2 h, respectively, after a heating rate of 5 °C min⁻¹. After cooling down to room temperature, the sample was subjected to a 6 M hydrochloric acid treatment to further remove the Fe
residue, and the final N-S-CMK-3 was obtained by washing with deionized water to a pH of 7 and drying at 60 °C for 12 h. Single-doped N-CMK-3 and S-CMK-3 were synthesized by using similar method discussed above without thiophene or NH3 dopants, respectively.

2.2 Material Characterization

Composition was measured using an inductively coupled plasma mass spectrometry (ICP-MS, PerkinElmer). The sample was prepared by dissolving 10 mg of catalyst in 4 mL of fresh aqua regia, followed by diluting to 250 mL with deionized water (18.2 MΩ). The XRD patterns were obtained from a Rigaku Ultima IV X-ray diffraction (XRD) systems with Cu Kα radiation (λ = 1.5406 Å), with a tube current of 44 mA and a tube voltage of 40 kV. JEOL 2100 200 kV scanning and transmission electron microscope (STEM) and corresponding element energy-dispersive X-ray spectrometer (EDS) were utilized to determine the catalyst structure and element concentration. JEOL 5800LV and FEI Quanta 250 field-emission scanning electron microscope (SEM) were used for macro morphology determination. X-ray photoelectron spectroscopy (XPS) with Mg Kα alpha X-ray (1253.6 eV) (Kratos Amicus/ESCA 3400) was also used to determine the heteroatom concentrations and its corresponding status through different binding energy peak. Surface area and porosity characterization were performed via nitrogen physisorption in a Micromeritics ASAP 2020 operated at -196 °C. The specific surface areas were calculated using the Brunauer-Emmett-Teller (BET) equation and the pore volume was determined at a relative pressure of 0.973. A DXR Raman microscope (Thermo Scientific, Waltham, MA, USA) was used for spectra acquisition with 780 nm excitation at 14 mW laser power, 10× objective, and 50 μm slit aperture (resolution is 4-8 cm⁻¹). The exposure time is 30 s.

2.3 Electrocatalytic Characterization

The electrochemical tests were carried out both in the half-cell and fuel cell reactors. The half-cell test was conducted in a three-electrode setup consisting of a rotating disk electrode (working electrode), a coiled platinum counter electrode, which was isolated by a fritted glass tube from the main test electrolyte, and a Hg/HgO reference electrode with 0.1 M KOH filling solution. Potential was applied by using a multi-channel potentiostat ( Biological). To fabricate the working electrode, a 2.0 mg ml⁻¹ solution of catalyst ink was prepared by dispersing N-S-CMK-3 in mixture of iso-propanol and 5 wt% Nafion solution (one-propanol : Nafion = 9 : 1), followed by ultrasonication until no aggregation was visible. Then, 30 μL of ink was dropped onto the surface of a glassy carbon electrode with a catalyst loading of 0.306 mg cm⁻², and a uniform catalyst film was obtained after 30 min ambient temperature drying in air. In order to compare the ORR performance of N-S-CMK-3 to other control samples, the electrodes of Pt/C, CMK-3 and mono-element doped CMK-3 were fabricated by using the same method discussed above. The ORR performance of the catalyst was investigated by cyclic voltammetry (CV) test, which was performed at 50 mV s⁻¹ scan rate after purging the electrolyte with N₂ and O₂ for 30 min respectively, followed by the linear sweep voltammetry (LSV) toward ORR activity evaluation in O₂-saturated electrolyte with 10 mV s⁻¹ scan rate at different rotating rate from 2000 rpm to 400 rpm. All experimental results for the ORR activity in this paper were reported as current density versus applied potential (vs RHE), and the current densities were normalized using geometric surface area of a glassy carbon electrode with 5 mm diameter. The Hg/HgO reference electrode was calibrated with respect to the reversible hydrogen electrode (RHE) before use. The calibration was conducted in standard three-electrode system with Pt wire as the working and counter electrodes, and the Hg/HgO electrode as the reference electrode. The 0.1 M KOH electrolyte was purged and saturated with high purity H₂ for 30 min before calibration, and LSV test was then run at a scan rate of 0.5 mV s⁻¹, and the potential range of -0.93 V to -0.85 V vs Hg/HgO, where the current crossed zero is taken to be the thermodynamic potential for the hydrogen electrode reactions. The result is E(RHE) = E(Hg/HgO) + 0.888 V in 0.1 M KOH electrolyte.

The fuel cell tests were performed on a Scribner Fuel Cell System 850e (Scribner Associates, USA), and the fuel cell fixture with an active area of 5 cm² was purchased from Fuel Cell Technology Inc. The cathode electrode composed of 70 wt% N-S-CMK-3 catalyst and 30 wt% AS-4 ionomer was mixed and directly sprayed onto an A-201 anion exchange membrane to obtain a catalyst loading of 2.0 mg cm⁻², while commercial Pt/C blended with 5 wt% PTFE solution (Pt/C : PTFE = 9 : 1) was sprayed onto a PTFE-untreated carbon cloth liquid diffusion layer with a 1.0 mg cm⁻² catalyst loading. The membrane electrode assembly (MEA) was constructed by pressing the anode carbon cloth with anion exchange membrane, which has been sprayed with cathode catalyst. 2.0 M KOH with 1.0 M fuel (glycerol, ethanol or sorbitol) was pumped into the anode compartment at 1.0 ml min⁻¹, while high purity O₂ (99.999%) regulated at 400 ml min⁻¹ was fed to cathode side with 30 psi backpressure. The cell temperature was kept at 50 °C, and the relative humidity for both anode and cathode is 100 %. The MEA was activated at 0.1 V cell voltage until the current density got stable. The I-V polarization curve was obtained by applying a constant voltage and collecting corresponding current density.

The overall electron transfer numbers per oxygen molecule involved in the typical ORR process were calculated from the slopes of the Koutecky-Levich plots using the following equations:14,30,51

\[ i = \frac{1}{j_L} + \frac{1}{j_k} = \frac{1}{B D^{1/2}} + \frac{1}{j_k} \]  

\[ B = 0.2nFC_o(D_o)^{2/3}D^{-1/6} \]  

\[ j_k = nFkC_o \]  

\[ J = \frac{1}{B D^{1/2}} + \frac{1}{j_k} \]  

\[ n = \frac{v}{S} \]
3 Results and discussion

3.1 Material synthesis and characterization

The well-ordered mesoporous carbons, N-S-CMK-3, were synthesized via carbonization and subsequent N and S doping processes, as shown in Scheme 1. Glucose served as the carbon source to mix with the mesoporous SBA-15 silica template, prior to calcination. Hydrofluoric acid (HF) was used to etch away the SBA15 template to obtain pure CMK-3 mesoporous carbons. Then, a mixture of CMK-3 and thiophene as well as iron(III) chloride (FeCl3) was annealed at 800 °C under anhydrous ammonia (NH3) gas purging, to facilitate heteroatom N and S doping into the graphitic framework of CMK-3. The N-S-CMK-3 mesoporous carbons were finally exposed to hydrochloric acid (HCl) washing and overnight vacuum drying (For synthesis details, see Experimental section).

In this work, glucose was chosen as the carbon precursor for mesoporous carbon synthesis owing to its unbranched carbon structure that facilitates formation of a stable and well-ordered mesoporous structure with narrow pore size distribution through carbonization. Glucose can be ubiquitously obtained in large quantities at low price, while some previously reported heteroatom-containing carbon precursors (e.g. Ferrocene, Vitamin B12, PDI) have 10 fold higher price. Together with its additional advantages of non-toxicity and non-volatility, glucose is a promising green carbon precursor for mesoporous carbon synthesis. We chose ammonia and thiophene as the N and S dopant precursors based on consideration of their small molecular weight, simple molecular structure and high N/C and S/C ratios (1.0 and 0.5, respectively). These precursors can not only largely prevent pore clogging by CN and CS species in the doping process, but also facilitate formation of high N and S content mesoporous carbon with very large surface area (>1000 m² g⁻¹), since ammonia etching can assist in the formation of extra macropores (pore diameter > 200 nm). Single and multi-doped CMK-3 carbons were prepared for comparison through the same processes as described above, and a commercial Pt/C, the best-known ORR catalyst, was also studied as the baseline performance in this work.

The as-synthesized mesoporous N-S-CMK-3 catalysts were first characterized using scanning electron microscopy (SEM), as shown in Figure 1a. The morphology of the N-S-CMK-3 was irregular with visible macropores on the surface, which had no distinguishable morphology change compared with that of CMK-3 (Figure S1). The underlying highly organized hierarchal porous structures were observed by transmission electron microscopy (TEM) characterization (Figure 1b). The TEM images revealed an average carbon rod diameter of 6 nm, which is consistent with the pore size of the SBA-15 template (inset in Figure S3a), indicating successful carbonization of glucose within the silica template. However, it is interesting to note that the carbon structure varied when the heteroatom doping temperature increased from 700 °C to 900 °C (Figure S2). At a doping temperature of 700 °C, apparent clogging from the thiophene derived CS species during the doping process became more serious and the carbon sheets were randomly formed, which could undesirably decrease the surface area and pore volume of carbon catalysts, leading to a ORR performance drop. The doping temperature of 900 °C appeared to facilitate the decomposition of the mesoporous carbon and a resulting porous structure was dominantly observed instead of the organized hierarchical porous structures (Figure S2), because of the overreaction of ammonia with carbon during the heteroatom doping process. Ammonia etching of the carbon may follow the reactions shown below:

$$2NH_3 \rightarrow N_2 + 3H_2$$  \hspace{1cm} (4)

$$C + 2H_2 \rightarrow CH_4$$  \hspace{1cm} (5)

The ammonia etching can be regulated by tuning the
doping temperature. A moderate etching rate at around 800 °C (doping temperature) favors the formation of macropores and not only diminishes the CS species clogging effect, but also significantly increases the surface area of the resulting N-S-CMK-3 mesoporous carbon. To better investigate the temperature effect on catalysts structure, the BET surface areas of the N-S-CMK-3 catalysts were measured to be 784 m² g⁻¹ (N-S-CMK-3 700 °C), 1023 m² g⁻¹ (N-S-CMK-3 800 °C) and 921 m² g⁻¹ (N-S-CMK-3 900 °C), all of which were lower than the 1126 m² g⁻¹ of CMK-3, but much higher than previously reported carbon nanotube and graphene ORR catalysts, such as mesoporous graphene and carbon hybrids.⁵,¹⁷ (the BET surface area and total pore volume of all the as-synthesized CMK-3 based catalysts are shown in Table S1). Therefore, 800 °C was determined to be the optimal doping temperature to prepare well-ordered mesoporous N-S-CMK-3. The surface texture of the N-S-CMK-3 catalysts was investigated by N₂ adsorption-desorption isotherms (type IV), and the typical hysteresis loops was observed to reveal the mesoporous nature of the well-ordered N-S-CMK-3 catalysts. The pore diameter of N-S-CMK-3 was centered at 3.7 nm according to the Barrett-Joyer-Halenda (BJH) model (inset in

Fig. 1 (a) SEM image (b) TEM image and (c) Nitrogen adsorption-desorption isotherms and pore size distribution (inset) of N-S-CMK-3 800 °C; (d) Small-angle XRD patterns of N-S-CMK-3 800 °C and CMK-3; (e) Raman spectra of N-S-CMK-3 800 °C, N-SMK-3, S-CMK-3 and CMK-3.
Figure 1c,38 which is close to the dominant pore diameter of 3.8 nm for pure CMK-3 (inset in Figure S3b); whereas larger mesopores with pore size ranging from 4.8 nm to 15.0 nm and macropores (>200 nm) were only obtained in N-S-CMK-3 after heteroatom doping. This wide pore size distribution further confirms the ammonia etching reaction with the N-S-CMK-3 mesoporous carbon. Zhang et al. reported that the combination of macropores and large mesopores could enhance the rate of desolvation and adsorption of O2 and increase the electrocatalytic activity for ORR.39 Consistent with that report, the N-S-CMK-3 (800 °C) with the unique mesoporous and extra macroporous structures exhibits the highest ORR performance among all investigated CMK-3 based catalysts as shown in section 3.2.

The well-ordered mesoporous carbon structure was also verified by wide-angle XRD measurement, as shown in Figure 1d. Two broad diffraction peaks centered at 25° and 44°, corresponding to the graphite (002) and (101) facets,30 were observed for both the N-S-CMK-3 and CMK-3 XRD patterns, indicating no significant structure change during the N-, S-doping process, and that the obtained N-S-CMK-3 mesoporous carbons were predominantly amorphous. More structural information for N-S-CMK-3 was obtained from Raman spectroscopy (Figure 1e). Two typical bands observed at 1340 cm−1 and 1580 cm−1 can be assigned to the D- and G-bands, corresponding to the disordered carbon structure and interplane sp2-hybridized graphitic carbon sheet, respectively.30,40 The I D / I G ratio of N-S-CMK-3 is similar to that of CMK-3 and lower than that of N-CMK-3 and S-CMK-3, suggesting a more graphitic structure with relatively low defect sites for the N-S-CMK-3 sample.

To determine heteroatoms content in as-synthesized N-S-CMK-3, catalysts were characterized by energy-dispersive X-ray spectroscopy (EDS). The EDS spectra reveal the presence of N, S and O atoms in the graphitic framework, while no Fe signal was observed (Figure S5a), indicating the Fe was removed by hydrochloric acid (HCl) washing and the high ORR activity could be only ascribed to the N-S-CMK-3 catalyst. Moreover, the EDS elemental mapping in conjunction with the TEM images illustrates a homogeneous distribution of N and S in the N-S-CMK-3 catalyst (Figure S5b-d). X-ray photoelectron spectroscopy (XPS) was further used to characterize N, S and O valence states. From Figure 2a, the content of the elements were determined by XPS to be 3.84 atom% of N, 0.83 atom% of S and 1.14 atom% of O, and negligible 0.12 atom% of Fe in N-S-CMK-3 for the 800 °C heteroatom doping temperature. Although the small amounts of Fe were quantified, no Fe signal was observed using the high-resolution spectrum of XPS (Figure S5a), suggesting the removal of Fe through HCl washing. The Fe result from XPS could be due to the signal to noise resolution limitation of XPS. The high-resolution S 2p spectrum was found to be fitted into two peaks centered at 163.5 eV and 165.0 eV, representing to S 2p 3/2 and S 2p 1/2; whereas O 1s groups, which have been reported inactive for ORR, was not found (Figure 2b).41,42 Similarly, the high-resolution N 1s spectra showed three nitrogen forms existed, which can be typically illustrated as pyridinic-N (398.3 eV), pyrrolic-N (399.9 eV), graphitic-N (401.2 eV) and N′-O (403.6 eV) structures, as shown in Figure 2c.19,28,43 The C 1s high-resolution spectrum was deconvoluted into single peaks corresponding to 284.5 eV (C1) for sp2-hybridised carbon atoms bonded to neighboring carbon and hydrogen atoms, 285.5 eV (C2) for C-N-C and C-S-C, and 288.0 eV (C3) for different oxygen-containing groups (e.g. COOH, C=O, and C-OH),28 further confirming that N and S were successfully doped into the CMK-3 carbon framework (Figure S5b). Inductively coupled plasma-mass spectrometry (ICP-MS) was also used to further test the content of Fe residue in N-S-CMK-3 catalysts. The Fe concentration was detected as only 0.09 wt%, which is close to the ICP-MS detection limit, further indicating successful Fe elimination for the N-S-CMK-3 mesoporous carbon.

3.2 Electrocatalytic analysis in half cell

![Figure 2](image-url) (a) XPS survey spectrum; high-resolution spectra of (b) S 2p and (c) N 1s of N-S-CMK-3 800 °C.
Before electrocatalytic ORR activity investigation, the Hg/HgO reference electrode was calibrated with respect to the reversible hydrogen electrode (RHE), and the result is $E_{\text{RHE}} = E_{\text{Hg/HgO}} + 0.888 \, \text{V}$ in 0.1 M KOH electrolyte, as shown in Figure S6. All applied potential reported in this paper was versus the reversible hydrogen electrode (RHE).
The ORR electrocatalytic activity of N-S-CMK-3 was first investigated by cyclic voltammetry (CV) tests, as shown in Figure S7. Featureless voltammetric currents without an obvious redox peak were obtained when the 0.1 M KOH electrolyte was saturated with N₂ (short dash curve), as a result of the well-known typical capacitance effect on porous carbon materials. In contrast, when an O₂-saturated electrolyte was used, a well-defined cathodic ORR peak, centered at 0.66 V with 5.45 mA cm⁻² current density, was observed over as-synthesized N-S-CMK-3, demonstrating obvious ORR electrocatalytic activity. To obtain deeper insight of ORR steps on the N-S-CMK-3 catalysts, linear sweep voltammetry (LSV) tests were carried out at different rotating rate ranging from 2000 rpm to 400 rpm in 0.1 M KOH electrolyte saturated with O₂ (Figure 3a). Comparative studies of N-S-CMK-3 with different doping temperature, single doped N-CMK-3, S-CMK-3, and CMK-3 as well as with Pt/C were also conducted using the same LSV method (Figure 3b and 3c). The
voltagemetric profiles demonstrate the current density increased as the applied potential became more negative. The Koutecky-Levich plots were obtained to be a linear line, indicating a typical first order ORR in a wide potential range (inset in Figure 3a). It has been found that the heteroatom doping temperature has strong influence on the ORR activity of the N-S-CMK-3 catalysts. Among all the investigated N-S-CMK-3 catalysts, the 800 °C N-S-CMK-3 displays the best ORR performance, which is comparable to the best-known ORR catalyst Pt/C, and much higher than the N-CMK-3 and S-CMK-3. In addition, only a 33 mV half-wave potential difference (ΔE1/2) between the N-S-CMK-3 and Pt/C catalysts, suggests that the dual-doped N-S-CMK-3 has promising potential to be an alternative to Pt/C (inset in Figure 3b). This remarkable ORR activity enhancement could be attributed to the high surface area of 800 °C N-S-CMK-3 (1023 m² g⁻¹), the synergistic effect of N and S, and the accessibility to large quantities of catalytic active sites. The corresponding Koutecky-Levich plots (J¹ vs ω¹/²) with various applied potentials exhibit a high linearity (inset Figure 3a, for K-L equation details see Experimental section), and the slopes among investigated applied potentials were approximately constant, indicating the electron transfer number per oxygen for ORR, n, are similar under different potentials. Consequently, all n of N-S-CMK-3 calculated at different applied potential were 4.0, which suggests a complete ORR with 4e⁻ transferred reduction to H₂O. We also investigated n and the kinetic limiting current density (Jk) of single doped N-CMK-3, S-CMK-3, CMK-3 as well as Pt/C at 0.5 V by using the K-L equation and the results are displayed in Figure 3d. Although both N-CMK-3 and S-CMK-3 show moderate performance for ORR with n of 3.0 and 2.8 at 0.5 V, only N-S-CMK-3 showed elegant ORR activity with complete 4e⁻ pathway (n=4) as comparable to Pt/C. Remarkably, the Jk of N-S-CMK-3 (32.6 mA cm⁻²) slightly surpassed that of Pt/C (25.6 mA cm⁻²) at 0.5 V and was much higher than that of N-CMK-3, S-CMK-3 and CMK-3. Obviously, the 4.0 electron transfer number and the highest kinetic limiting current density suggest the potential of the reported N-S-CMK-3 as a Pt/C alternative for ORR in fuel cell.

Since the N-S-CMK-3 will be used as the cathode catalyst in direct alcohol fuel cell, the catalyst durability and alcohol fuel crossover influence on ORR should be considered. The durability of the catalysts was first tested by cycling the catalyst between 0.1 V and 1.2 V at 10 mV s⁻¹ scan rate under oxygen purging. After 3000 potential cycles, the N-S-CMK-3 exhibits a robust stability with only 46 mV of half-wave potential shift (Figure 4a), which is superior to 52 mV for the commercial Pt/C catalyst (Figure S8). The stability of N-S-CMK-3 was further measured at a constant voltage of 0.5 V for 45000 s (12.5 hours). The results indicate slowly decreasing ORR performance with N-S-CMK-3 as 85.9% of the current was maintained after 45000 s. Conversely, Pt/C exhibits more serious performance degradation as only 76.1% of the current remained after an identical stability test (Figure S9). For fuel-crossover tolerance, glycerol, the coproduct (about 10 wt%) from biodiesel manufacturing, was added into the half cell reactor with the N-S-CMK-3 catalysts after 1800 s (chronoamperometry test at 0.6 V); comparative study of Pt/C catalysts was also carried out using the same method. Interestingly, when glycerol was added into electrolyte, the current density of N-S-CMK-3 had nearly no change, strongly indicating its high catalytic activity for ORR while being nearly inert towards glycerol oxidation (Figure 4b). Conversely, Pt/C exhibits an instantaneous current density spike due to its high activity toward glycerol oxidation, and thus its vulnerability to glycerol crossover.

3.3 Electrocatalytic analysis in single fuel cell

- Figure 4 (a) Polarization curves of N-S-CMK-3 800 °C before and after 3000 potential cycles in O₂-saturated 0.1M KOH solution; (b) Glycerol crossover tolerance test of N-S-CMK-3 800 °C and commercial Pt/C conducted by chronoamperometric response at 0.6 V vs RHE.
Single fuel cell performance is considered the ultimate catalyst evaluation method from both engineering and application points of view. The N-S-CMK-3 was fabricated into an alkaline membrane fuel cell, and its electrocatalytic activity toward ORR and single glycerol fuel cell performance tested. The steady-state polarization curves with different cathodic catalysts in the glycerol alkaline fuel cell are shown in Figure 5a. It is observed that the open circuit potential of the fuel cell with N-S-CMK-3, CMK-3 and Pt/C were 0.86 V, 0.70 V and 0.85 V, respectively. Due to the outstanding ORR electrocatalytic activity and apparent O₂ diffusion advantage, the glycerol alkaline membrane fuel cell with N-S-CMK-3 cathode yields a high peak power density of 88.2 mW cm⁻², which is much higher than that with the CMK-3 cathode, 42.4 mV cm⁻², and 84% of the fuel cell performance when compared with the best-known ORR catalyst, Pt/C, at cathode (105 mW cm⁻² peak power density). It is worth to mention that the Fe loading would be extremely low (2.4 μg cm⁻² cathode) as converted from 0.12 wt% of Fe determined by XPS. Based on the I-V curve analysis, the fuel cell with N-S-CMK-3 cathode displays Pt-like behavior both in kinetic dominated regime (current density < 50 mA cm⁻²) and ohmic resistant controlled regime (current density > 50 mA cm⁻²), implying a considerably high ORR activity and less performance loss owing to the resistance to ionic current.

We also tested the fuel cell performance using other bioalcohol fuels, ethanol and sorbitol. Ethanol is the first generation of biofuel and has been widely used as gasoline additive, while sorbitol is an important sugar alcohol that can be produced from cellulose hydrolysis and potentially used as precursors to generate the biorenewable chemicals. The N-S-CMK-3 cathode alkaline fuel cell reached 80% of that with the Pt/C cathode alkaline fuel cell using sorbitol, and even higher than that of Pt/C when ethanol is used as the fuel (Figure S10). It should be noted that the catalyst layer for N-S-CMK-3 cathode is thicker than that for Pt/C, which could affect the O₂ diffusion toward ORR on fuel cell cathode side, leading to a slightly lower peak power density for N-S-CMK-3 cathode fuel cell relative to the Pt/C cathode one. To further study the O₂ diffusion effect, different backpressures (30 psi and ambient pressure) were used. From Figure S11, the peak power density of N-S-CMK-3 cathode glycerol fuel cell was obtained as 82.7 mW cm⁻², which has only 6.2% performance dropping in contrast to the 88.2 mW cm⁻² achieved by using 30 psi backpressure. Thus, the O₂ diffusion issue is negligible when the backpressure changes from 30 psi to ambient pressure. This good O₂ diffusion property can likely be attributed to its uniform mesoporous structure with a wide range of mesopores and macropores as well as the high surface area.

The durability of catalyst also serves as an important criterion to determine the suitability of N-S-CMK-3 in the cathodic side for ORR. As shown in Figure 5b, the glycerol fuel cell shows 90.6 mW cm⁻² of peak power density after the 2 h scan current test, which is even slightly higher than the 88.2 mW cm⁻² during initial performance and indicates robust stability and high selectivity to ORR in cathode of glycerol fuel cell. In contrast, the performance of the Pt/C cathode glycerol fuel cell was decreased dramatically from 105 mW cm⁻² to 66.3 mW cm⁻² (36.9% performance dropping) after 2 h, consistent with the ORR performance drop in the half cell fuel-crossover test, because glycerol could be readily oxidized on the Pt/C catalysts surface thereby decreasing the fuel cell performance after the fuel-crossover. Together with the excellent ORR performance in the glycerol alkaline fuel cell, good O₂ diffusion and expected durability, the as-synthesized N-S-CMK-3 could effectively serve as the cathodic catalyst in alkaline fuel cell.

### 3.4 Insights into the synergistic effect of N and S on ORR
To acquire the insight into synergistic effect of N and S heteroatoms on ORR activity, all of the CMK-3-based catalysts were characterized by XPS. The N/C and S/C atomic ratios were both significantly decreased from 6.40 atom% to 1.27 atom% and 1.11 atom% to 0.20 atom%, respectively, when the doping temperature was increased from 700 °C to 900 °C (Figure S12 and Table S1), which is similar to previous reports.

The broad N1s peak was then deconvoluted into four peaks, assigned to pyridinic-N, pyrrolic-N, graphitic-N and N'-O (inactive to ORR) structures, respectively (Figure S12 and Figure 2C). Interestingly, when combined with the ORR performance and electron transfer number, n, for the N-S-CMK-3 catalysts (Figure 3b), Figure 6 reveals a correlation between the graphitic-N species and the ORR activity. For example, the N-S-CMK-3 (800 °C) with a higher proportion of graphitic-N centers favors higher ORR activity with complete 4e⁻ transferred reaction, whereas those containing a lower portion of graphitic-N sites exhibit lower ORR activity for both the 4e⁻ and 2e⁻ reactions. In addition, although the graphitic-N content has been found to be close to N-CMK-3 and N-S-CMK-3 (Figure 6b), the N-CMK-3 without S doping exhibits moderate ORR activity with n of 3.0 at 0.5 V, which is much lower than that of N and S dual-doped N-S-CMK-3. Thus, it could be hypothesized that the doped graphitic-N and S atoms can increase both the catalyst activity toward ORR and the synergistic effect between N and S, thus greatly enhancing the ORR activity when combined in the N-S-CMK-3 catalysts. Qiao et al. carried out density functional theory (DFT) calculation to study synergistic effect of N and S on ORR performance. The dual-doping graphitic-N and S into the carbon framework provides asymmetric spin and alters the charge density and spin density of neighbor carbon atom owning to the high electronegativity of N, 3.04 and a mismatch of the outermost orbitals of S; thus, it significantly uplifts the ORR activity. Based on the DFT calculation results discussed above, the graphitic-N and S cooperated in our N-S-CMK-3 could bring more ORR active sites and promote the catalyst’s ORR activity to achieve comparable performance to the Pt/C catalyst.

Conclusions

In summary, we have demonstrated the successful synthesis of novel N- and S- dual-doped N-S-CMK-3 mesoporous carbons using biorenewable glucose as the carbon source and ammonia and thiophene as highly efficient N and S dopants. The high surface area (1023 m² g⁻¹), derived from a moderate NH₃ etching effect, and the synergistic effect of graphitic-N and S atoms resulted in remarkable electrocatalytic ORR activity. N-S-CMK-3 annealed at 800 °C exhibits the highest ORR activity (close to that of Pt/C) with 4.0 electron transfer number per oxygen and kinetic-limiting current density of 32.6 mA cm⁻² at 0.5 V (vs RHE). By directly using N-S-CMK-3 as the cathode catalyst in single direct glycerol fuel cell, it exhibited 88.2 mW cm⁻² peak power density without obvious O₂ diffusion limitation, which represents 84% of the initial performance of the one with a Pt/C cathode. More interestingly, the peak power density of the fuel cell with N-S-CMK-3 can maintain a peak power density at 90.6 mW cm⁻² after two hours operation, while the one with Pt/C cathode lost its peak power density to 66.3 mW cm⁻².

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Notes and references


