



# Implementing PGM-free electrocatalysts in high-temperature polymer electrolyte membrane fuel cells

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## ABSTRACT

Polymer Electrolyte Membrane Fuel Cells (PEMFCs) face numerous challenges, involving the membrane nature and the active material for the cathodic reaction. A way to achieve more efficient PEMFCs is to increase their operating temperature above 373 K: High-Temperature PEMFCs (HT-PEMFCs). In this communication, we introduce for the first time the use of platinum group metal-free electrocatalysts (PGM-free) for oxygen reduction reaction (ORR) in HT-PEMFC, namely an iron-nitrogen-carbon (Fe-N-C) electrocatalyst synthesized by the sacrificial support method and discuss their performances. A cell voltage of 0.43 V was observed at  $0.2 \text{ A cm}_{\text{geo}}^{-2}$ , this activity being greatly improved by increasing the back-pressure of the PEMFC (from 0.0 to  $3.0 \times 10^5 \text{ Pa}$ ), reaching a polarization of 0.65 V at  $0.2 \text{ A cm}_{\text{geo}}^{-2}$  (at 433 K,  $\text{O}_2$  at the cathode), thus proving that the main limitations of the HT-PEMFC with a Fe-N-C cathode were not induced by the intrinsic activity of the electrocatalyst, but by the transport of the oxygen throughout the electrocatalyst structure.

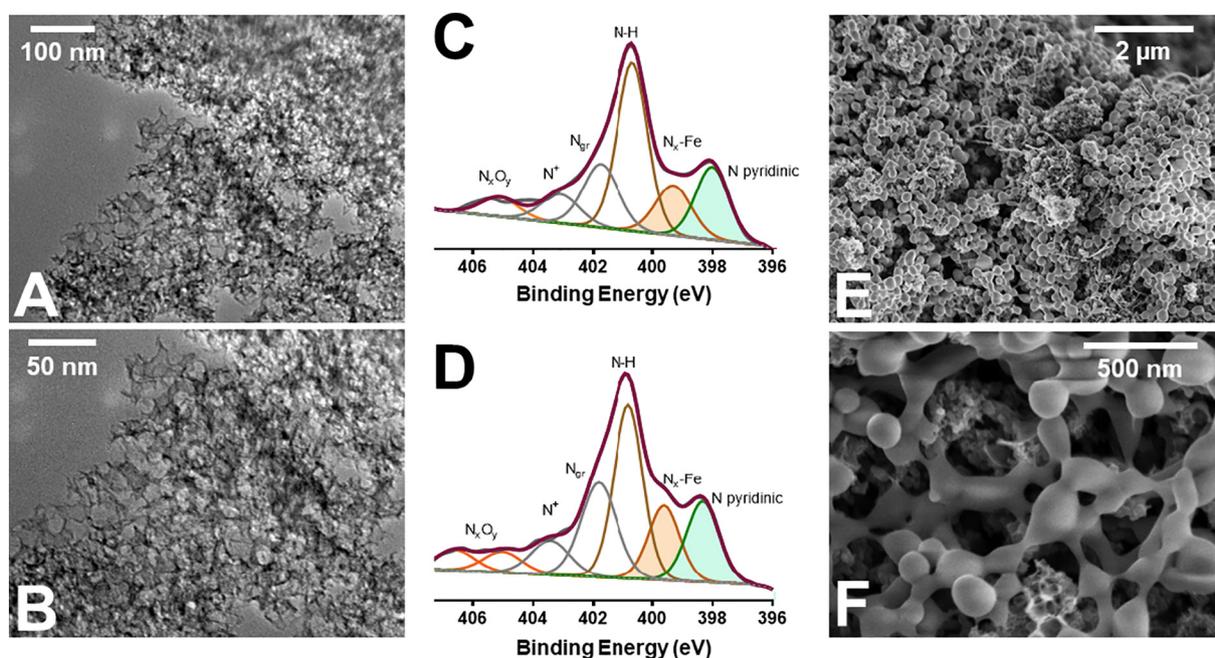
## 1. Introduction

In contrast to Polymer Electrolyte Membrane Fuel Cells (PEMFCs), which operate at *ca.* 353 K, High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFCs) operate at temperatures higher than 393 K. There are several advantages to use HT-PEMFCs due to the higher operating temperature, *i.e.*, (i) a kinetic enhancement of the otherwise sluggish oxygen reduction reaction (ORR) at the cathode, resulting in the possibility of using non-platinum group metal catalysts (ii) a decrease of the CO adsorption on Pt electrocatalysts, thereby increasing tolerance and decreasing the poisoning effect, (iii) a better heat and water management, *i.e.*, no flooding of the membrane due to the gaseous form of the produced water [1–4]. Despite these advantages, significant limitations in the practical use of HT-PEMFCs drive extensive ongoing research in various aspects, as the stability and activity of the cathode electrocatalysts and the development of high-performance membranes for HT-PEMFCs [5–8]. Indeed, the high temperature of operation decreases conductivity and durability of traditionally used membranes in PEMFCs (*e.g.*, Nafion®) as the evaporation of water from the membrane results in a loss in ionic conductivity and concurrent loss in power density [1–4,9,10]. Specifically, the use of phosphoric acid as a dopant for the polymer membrane results in a high thermal stability and proton conductivity, thus reaching the US

Department of Energy criteria for HT-PEMFCs [1]. To address the issues related to the ORR electrocatalysts in HT-PEMFCs, it is essential to explore alternative electrocatalysts, such as PGM-free Fe-N-C. They have been extensively studied for application in low-temperature PEMFCs, resulting in several new technological breakthroughs [11–15]. Although their potential has been previously postulated owing to enhanced ORR kinetics at high temperature, higher tolerance to impurities and smaller oxidation, there has been no real effort in the development of Fe-N-C catalysts for high-temperature PEMFCs, with the exception of the recent work of Hu *et al.* [16]. In this work, we successfully demonstrate the application of Fe-N-C catalyst in Membrane Electrode Assemblies (MEAs) fabricated for HT-PEMFCs. The Fe-N-C catalyst (discussed as NCMI, because of the precursors used during its synthesis process, *i.e.* Nicarbazine – N, Carbendazim – C, Methyl-Imidazole – M and Imidazolin Urea – I) used in this work was based on the UNM-developed sacrificial support method (SSM – see [Materials & methods](#)). Such electrocatalysts, because of their high crystallinity [17,18] were believed to be able to withstand the high temperature conditions of an HT-PEMFC. The electrocatalyst was characterized in a single-cell fuel cell. Although it presented lower performances than a Pt-alloy/C cathode characterized in the same conditions, the losses in activity originated mostly from the  $\text{O}_2$  transport in the NCMI nanostructure and not from the intrinsic activity of the nanostructure itself.

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**Fig. 1.** (A–B) TEM images of NCMI electrocatalyst at different magnifications. (C–D) XPS of the (C) NCMI electrocatalysts and (D) of the GDE. (E–F) SEM of the GDE at different magnifications.

**Table 1**

Elemental composition and nitrogen speciation determined from the XPS patterns for the NCMI electrocatalyst and the GDE.

		NCMI Electrocatalyst	GDE
Elemental composition	C 1s (%)	94.5	89.2
	F 1s (%)		3.8
	O 1s (%)	3.3	5.0
	Fe 2p (%)	0.1	
	N 1s (%)	2.1	2.0
Nitrogen speciation	N pyridinic (%)	18.2	15.2
	N <sub>x</sub> -Fe (%)	12.9	15.9
	N-H (%)	37.9	30.4
	Graphitic N (%)	17.1	19.5
	N <sup>+</sup> (%)	8.5	8.5
	NO (%)	5.3	10.6

## 2. Materials & methods

### 2.1. Catalyst synthesis

The NCMI catalyst was prepared by the Sacrificial Support Method (SSM) [12,19,20]. Briefly, wet mixing of a calculated amount of organic precursors: Nicarbazin (Sigma Aldrich, 12.5 g), Carbendazim (Sigma Aldrich, 97%, 5 g), Methyl-Imidazole (Sigma Aldrich, 95%, 5 g) and Imidazolidinyl Urea (Sigma Aldrich, 2.5 g) was carried out with silica support (LM 150, Cab-O-Sil, 5 g) and iron salt (Fe(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O, Sigma Aldrich, > 98%, 2.5 g). The mixture was oven dried at 353 K and pyrolyzed at 1248 K for 45 min in a reductive atmosphere of H<sub>2</sub>/N<sub>2</sub> (7 at.% H<sub>2</sub>) in a tube furnace. The pyrolyzed material was then treated with an acid mixture of nitric acid and hydrofluoric acid to remove the silica template and metallic impurities. The catalyst was then washed several times with water until reaching pH = 7. A second heat treatment was then performed at 1223 K for 30 min in an ammonia atmosphere.

### 2.2. Catalyst ink and GDE preparation

The catalyst ink was prepared by mixing a calculated amount of catalyst in deionized water:isopropanol mixture (2:1 volume ratio). Polytetrafluoroethylene dispersion (PTFE, 0.06 g/mL) was added to

obtain a 25 wt% loading in PTFE in the catalyst layer. The prepared catalyst ink was sprayed on GDL (Sigracet GLD 29 BC) with dimensions of 7.6 cm × 7.6 cm, using a Spirit Air™ air gun. The GDL was positioned onto a heating plate ( $T = 333$  K) during the spraying to accelerate the drying. The final catalyst loading was 2 mg cm<sup>-2</sup>.

### 2.3. Membrane electrode assembly (MEA) preparation and fuel cell testing

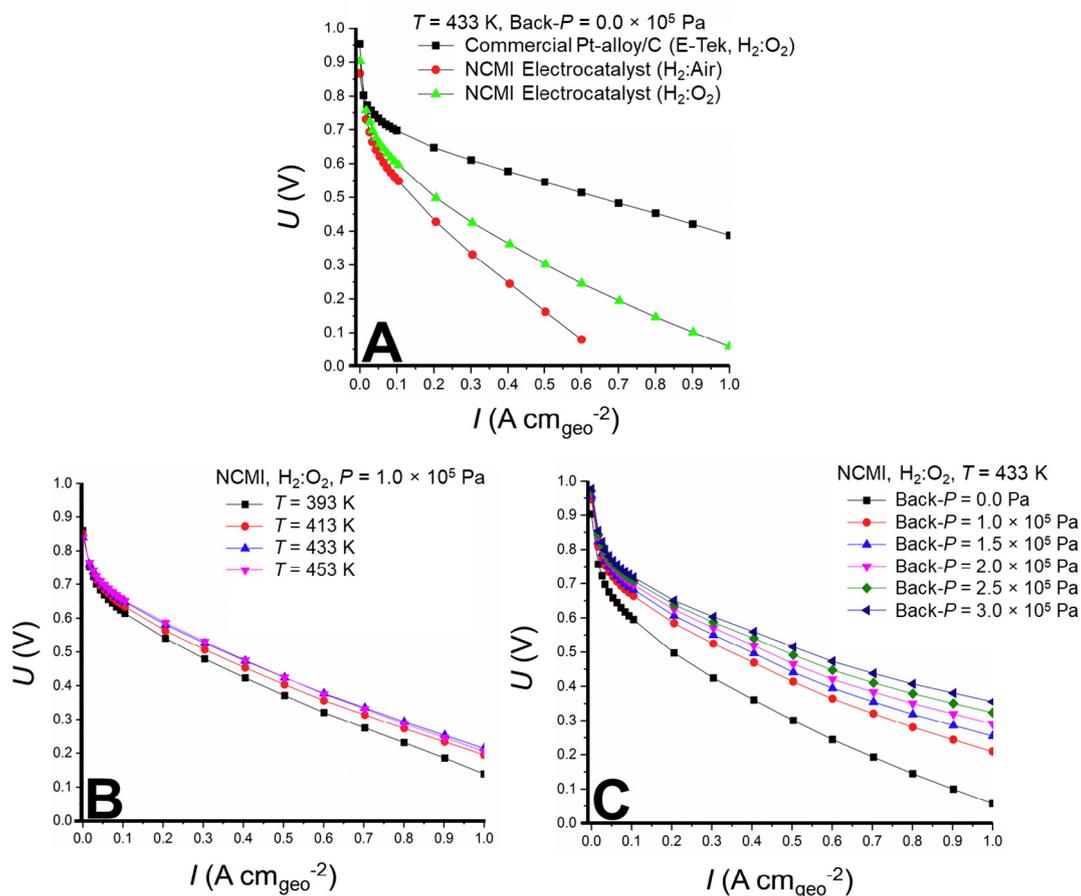
The prepared electrode was used as the cathode, and a commercial electrode (Pt/C from E-Tek) with platinum loading of 1.0 mg cm<sup>-2</sup> was used as the anode. The MEA was fabricated by hot-pressing a piece of membrane (p-PBI prepared using the PPA process [21–23]) between the two Kapton framed electrodes. The specific polymerization process used in this study was previously reported<sup>33</sup> and yielded a polymer (poly(2,2'-(1,4-phenylene)5,5'-bibenzimidazole)) with a polymer inherent viscosity of 3.5 dL g<sup>-1</sup>. After casting and hydrolysis at RH 55%, the membrane (250 μm thickness) displayed an ionic conductivity of 0.23 S cm<sup>-1</sup> at 160 °C. The MEA was then assembled into a single cell fuel cell testing hardware. The gas flow plates were graphite plates with double serpentine gas channels. Stainless steel end plates with attached heaters were used to clamp the graphite flow plates. A commercial fuel cell testing station (Fuel Cell Technology, Inc.) was used for fuel cell testing, while gases were fed to the anode and cathode without any humidification. The instrument was controlled by home-programmed Lab View Software (National Instruments, Austin, TX).

### 2.4. Characterization details

SEM and TEM images were obtained by Hitachi S-5200 instrument and JEM-2010, respectively. XPS was obtained using monochromated Al K $\alpha$  source at Kratos Axis Ultra DLD Spectrometer. Micromeritics Gemini 2360 instrument was used to obtain surface area value by Brunauer-Emmett-Teller (BET) analysis.

## 3. Results and discussion

First, the physical, morphological and compositional characteristics of the NCMI electrocatalyst were obtained by Brunauer-Emmett-Teller (BET) surface area determination, transmission electron microscopy



**Fig. 2.** (A) Fuel cell performance of NCMI electrocatalyst (using a commercial Pt/C anode with a Pt loading of  $1.0\ mg\ cm_{geo}^{-2}$ ) at 433 K, operated at atmospheric pressure, without humidification of the gases, no back pressure and of the commercial Pt-alloy/C electrocatalyst (Pt loading  $0.7\ mg\ cm_{geo}^{-2}$ ). Hydrogen supply = 500 sccm, oxygen or air supply = 400 sccm. (B) Effect of temperature on the performances of the NCMI electrocatalyst, with pure  $O_2$  provided at the cathode and no back-pressure was applied. (C) Effect of the back-pressure on the NCMI electrocatalyst performances, at 433 K and with pure  $O_2$  provided at the cathode.

(TEM) imaging and X-ray photoelectron spectroscopy (XPS). TEM images of the catalyst in Fig. 1A–B demonstrate its open frame morphology with the high surface area as evidenced by numerous pores of different dimensions present in its structure. BET surface area analysis confirms these microscopic observations estimating surface area to be *ca.*  $523\ m^2\ g^{-1}$ . The porous nature of catalyst morphology is extremely beneficial for efficient oxygen transport to active sites and water management [14]. The surface compositional analysis of the catalyst was performed by X-ray photoelectron spectroscopy (XPS). Table 1 and Fig. 1C–D show the elemental composition of the NCMI electrocatalyst itself and of the Gas Diffusion Electrode (GDE), *i.e.*, the electrocatalysts mixed with PTFE and sprayed on a Gas Diffusion Layer (GDL, see Materials & methods). For the electrocatalyst, a typical composition is observed with 2.1 at.% of nitrogen and 0.1 at.% of iron detected. When the GDE is prepared with the PTFE binder and the NCMI electrocatalyst, a 3.8 at.% of F is detected. Detection of Fe is not possible when fluorine is present as the Auger peak from fluorine overlaps with Fe 2p photoelectron line. The chemistry of nitrogen is similar to previous reports for M–N–C materials [12,13]. The electrocatalyst nitrogen atoms shows 18 at.% of pyridinic nitrogen and 13 at.% of Fe– $N_x$ . It has been previously established that pyridinic nitrogen and Fe– $N_x$  are the most catalytically active for the oxygen reduction reaction [24]. Upon making the electrode, the chemistry changes insignificantly, except for a decrease of N–H atomic content and a significant increase of the N–O atomic content. Importantly, pyridinic N and Fe– $N_x$  speciation remains close to the electrocatalyst speciation. Scanning electron microscopy (SEM) of the catalyst coated GDL (see Fig. 1E–F) was performed to

observe the morphology of the layer which contains the porous carbon catalyst and the PTFE binder. Higher resolution SEM image (Fig. 1F) shows the presence of high surface area catalyst along with spherical PTFE particles on the surface.

The HT-PEMFC performance was investigated in a single cell fuel cell. Fig. 2A shows the polarization curves of a fuel cell with the NCMI electrocatalyst at 433 K, operated at atmospheric pressure and dry gases without external humidification. At a current density of  $0.2\ A\ cm_{geo}^{-2}$ , a voltage of approximately  $U = 0.43\ V$  was obtained with hydrogen and air supplied at 500 and 400 sccm constant flows, respectively. When the oxidant gas was changed from air to oxygen, the cell voltage at  $0.2\ A\ cm_{geo}^{-2}$  increased from 0.43 V to 0.50 V. The fuel cell performance of a commercial MEA, with a Celtec-P membrane, the same anode but a Pt-alloy/C cathode ( $0.7\ mg_{Pt}\ cm_{geo}^{-2}$ ) was included for comparison (The HT-PEMFC with Pt alloy presented similar performances to those reported in the literature [25,26]). The NCMI electrocatalyst presented lower overall performances (*i.e.* 0.50 V for the NCMI cathode vs. 0.67 V for the Pt alloy cathode at  $0.2\ A\ cm_{geo}^{-2}$ ) and a higher performance loss in the low-current region, due to the slower kinetics of the ORR on Fe–N–C electrocatalysts with respect to Pt alloys. Higher performance losses were also observed in the medium-current region (*i.e.*,  $0.2$ – $0.8\ A\ cm_{geo}^{-2}$ ) where the current is mostly controlled by the ohmic losses and the  $O_2$  transport, thus showing that the cathode nanostructure can be optimized to enhance the transport of the reactive species (*i.e.*,  $O_2$  and  $H^+$ ) to the active sites. The effect of temperature on the NCMI electrocatalyst performances are shown in Fig. 2B. The fuel cell performances increased with increasing operating temperature

from 393 K to 433 K, with nearly constant performance from 433 K to 453 K. The effect of back-pressure [27] (*i.e.*, the pressure at the outlet of the fuel cell) on the NCMI electrocatalyst activity was investigated as shown in Fig. 2C. The performances substantially increased with the increase of back-pressure, thus showing that the O<sub>2</sub> transport was greatly limiting the performances of the NCMI electrocatalyst. Indeed, with a back-pressure of  $3.0 \times 10^5$  Pa, the polarization observed at 0.2 A cm<sub>geo</sub><sup>-2</sup> is close to the polarization observed for the Pt alloy/C cathode in Fig. 2A (*i.e.*, 0.65 V vs. 0.67 V, at 433 K, O<sub>2</sub> provided at the cathode). Thus, the performances can be improved by controlling and modifying the porosity network inside the active material. This can easily be performed using the sacrificial support method, as the size of the silica template is responsible for the size of the final porosities. Although it was not the focus of the manuscript, the stability of the HT-PEMFC was also investigated and showed a stable operation during 250 h, at 433 K, without gas humidification, with air provided at the cathode and an operating current density of 0.1 A cm<sub>geo</sub><sup>-2</sup>.

#### 4. Conclusion

A Fe-N-C electrocatalyst (NCMI) was successfully implemented as a cathode in a high-temperature polymer electrolyte membrane fuel cell. A polarization of 0.43 V was observed at 0.2 A cm<sub>geo</sub><sup>-2</sup> (while being of 0.67 V for a HT-PEMFC with a Pt alloy cathode). The activity of the NCMI electrocatalyst was shown to be extremely dependent of the back-pressure applied to the cell (*i.e.*, at 0.2 A cm<sub>geo</sub><sup>-2</sup>,  $U = 0.43$  V without back-pressure and a voltage of 0.65 V with a back-pressure of  $3.0 \times 10^5$  Pa), therefore showing that the activity was not limited by the intrinsic activity of the NCMI electrocatalyst, but by the O<sub>2</sub> transport to the active sites.

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#### References

- [1] A. Chandan, M. Hattenberger, A. El-Kharouf, S. Du, A. Dhir, V. Self, B.G. Pollet, A. Ingram, W. Bujalski, High temperature (HT) polymer electrolyte membrane fuel cells (PEMFC)-a review, *J. Power Sources* 231 (2013) 264–278, <http://dx.doi.org/10.1016/j.jpowsour.2012.11.126>.
- [2] R.E. Rosli, A.B. Sulong, W.R.W. Daud, M.A. Zulkifley, T. Husaini, M.I. Rosli, E.H. Majlan, M.A. Haque, A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system, *Int. J. Hydrog. Energy* 42 (2017) 9293–9314, <http://dx.doi.org/10.1016/j.ijhydene.2016.06.211>.
- [3] Y. Shao, G. Yin, Z. Wang, Y. Gao, Proton exchange membrane fuel cell from low temperature to high temperature: material challenges, *J. Power Sources* 167 (2007) 235–242, <http://dx.doi.org/10.1016/j.jpowsour.2007.02.065>.
- [4] J. Zhang, Z. Xie, J. Zhang, Y. Tang, C. Song, T. Navessin, Z. Shi, D. Song, H. Wang, D.P. Wilkinson, Z.S. Liu, S. Holdcroft, High temperature PEM fuel cells, *J. Power Sources* 160 (2006) 872–891, <http://dx.doi.org/10.1016/j.jpowsour.2006.05.034>.
- [5] J.A. Mader, B.C. Benicewicz, Sulfonated polybenzimidazoles for high temperature PEM fuel cells, *Macromolecules* 43 (2010) 6706–6715, <http://dx.doi.org/10.1021/ma1009098>.
- [6] J.A. Mader, B.C. Benicewicz, Synthesis and properties of segmented block copolymers of functionalised polybenzimidazoles for high-temperature pem fuel cells, *Fuel Cells* 11 (2011) 222–237, <http://dx.doi.org/10.1002/fuce.201000085>.
- [7] A.L. Gullledge, B. Gu, B.C. Benicewicz, A new sequence isomer of AB-polybenzimidazole for high-temperature PEM fuel cells, *J. Polym. Sci. A Polym. Chem.* 50 (2012) 306–313, <http://dx.doi.org/10.1002/pola.25034>.
- [8] F. Seland, T. Berning, B. Børresen, R. Tunold, Improving the performance of high-temperature PEM fuel cells based on PBI electrolyte, *J. Power Sources* 160 (2006) 27–36, <http://dx.doi.org/10.1016/j.jpowsour.2006.01.047>.
- [9] C. Yang, P. Costamagna, S. Srinivasan, J. Benziger, A.B. Bocarsly, Approaches and technical challenges to high temperature operation of proton exchange membrane fuel cells, *J. Power Sources* 103 (2001) 1–9, [http://dx.doi.org/10.1016/S0378-7753\(01\)00812-6](http://dx.doi.org/10.1016/S0378-7753(01)00812-6).
- [10] S. Bose, T. Kuila, T.X.H. Nguyen, N.H. Kim, K.T. Lau, J.H. Lee, Polymer membranes for high temperature proton exchange membrane fuel cell: recent advances and challenges, *Prog. Polym. Sci.* 36 (2011) 813–843, <http://dx.doi.org/10.1016/j.progpolymsci.2011.01.003>.
- [11] F. Jaouen, V. Goellner, M. Lefèvre, J. Herranz, E. Proietti, J.P. Dodelet, Oxygen reduction activities compared in rotating-disk electrode and proton exchange membrane fuel cells for highly active FeNC catalysts, *Electrochim. Acta* 87 (2013) 619–628, <http://dx.doi.org/10.1016/j.electacta.2012.09.057>.
- [12] Y. Chen, R. Gokhale, A. Serov, K. Artyushkova, P. Atanassov, Novel highly active and selective Fe-N-C oxygen reduction electrocatalysts derived from in-situ polymerization pyrolysis, *Nano Energy* 38 (2017) 201–209, <http://dx.doi.org/10.1016/j.nanoen.2017.05.059>.
- [13] A. Serov, A.D. Shum, X. Xiao, V. De Andrade, K. Artyushkova, I.V. Zenyuk, P. Atanassov, Nano-structured platinum group metal-free catalysts and their integration in fuel cell electrode architectures, *Appl. Catal. B Environ.* (2017) 0–1, <http://dx.doi.org/10.1016/j.apcatb.2017.08.067>.
- [14] S. Stariha, K. Artyushkova, A. Serov, P. Atanassov, Non-PGM membrane electrode assemblies: optimization for performance, *Int. J. Hydrog. Energy* 40 (2015) 14676–14682, <http://dx.doi.org/10.1016/j.ijhydene.2015.05.185>.
- [15] A. Serov, K. Artyushkova, E. Niangar, C. Wang, N. Dale, F. Jaouen, M.T. Sougrati, Q. Jia, S. Mukerjee, P. Atanassov, Nano-structured non-platinum catalysts for automotive fuel cell application, *Nano Energy* 16 (2015) 293–300, <http://dx.doi.org/10.1016/j.nanoen.2015.07.002>.
- [16] Y. Hu, J.O. Jensen, C. Pan, L.N. Cleemann, I. Shypunov, Q. Li, Immunity of the Fe-N-C catalysts to electrolyte adsorption: phosphate but not perchloric anions, *Appl. Catal. B Environ.* (2018), <http://dx.doi.org/10.1016/j.apcatb.2018.03.056>.
- [17] M.J. Workman, A. Serov, L.K. Tsui, P. Atanassov, K. Artyushkova, Fe-N-C catalyst graphitic layer structure and fuel cell performance, *ACS Energy Lett.* 2 (2017) 1489–1493, <http://dx.doi.org/10.1021/acsenylett.7b00391>.
- [18] M.J. Workman, M. Dzara, C. Ngo, S. Pylypenko, A. Serov, S. McKinney, J. Gordon, P. Atanassov, K. Artyushkova, Platinum group metal-free electrocatalysts: effects of synthesis on structure and performance in proton-exchange membrane fuel cell cathodes, *J. Power Sources* 348 (2017) 30–39, <http://dx.doi.org/10.1016/j.jpowsour.2017.02.067>.
- [19] A. Serov, K. Artyushkova, P. Atanassov, Fe-N-C oxygen reduction fuel cell catalyst derived from carbendazim: synthesis, structure, and reactivity, *Adv. Energy Mater.* 4 (2014) 1–7, <http://dx.doi.org/10.1002/aenm.201301735>.
- [20] A. Serov, M.H. Robson, B. Halevi, K. Artyushkova, P. Atanassov, Highly active and durable templated non-PGM cathode catalysts derived from iron and aminoantipyrine, *Electrochem. Commun.* 22 (2012) 53–56, <http://dx.doi.org/10.1016/j.elecom.2012.04.029>.
- [21] L. Xiao, H. Zhang, E. Scanlon, L.S. Ramanathan, E.-W. Choe, D. Rogers, T. Apple, B.C. Benicewicz, High-temperature polybenzimidazole fuel cell membranes via a sol-gel process, *Chem. Mater.* 17 (2005) 5328–5333, <http://dx.doi.org/10.1021/cm050831>.
- [22] S. Yu, L. Xiao, B.C. Benicewicz, Durability studies of PBI-based high temperature PEMFCs, *Fuel Cells* 8 (2008) 165–174.
- [23] S. Yu, H. Zhang, L. Xiao, E.-W. Choe, B.C. Benicewicz, Synthesis of poly (2,2'-(1,4-phenylene) 5,5'-bibenzimidazole) (para -PBI) and phosphoric acid doped membrane for fuel cells, *Fuel Cells* 9 (2009) 318–324, <http://dx.doi.org/10.1002/fuce.200900062>.
- [24] K. Artyushkova, A. Serov, S. Rojas-Carbonell, P. Atanassov, Chemistry of multi-tetradentate active sites for oxygen reduction reaction in transition metal-nitrogen-carbon electrocatalysts, *J. Phys. Chem. C* 119 (2015) 25917–25928, <http://dx.doi.org/10.1021/acs.jpcc.5b07653>.
- [25] C.V. Rao, J. Parrondo, S.L. Ghatty, B. Rambabu, High temperature polymer electrolyte membrane fuel cell performance of Pt/Coy/C cathodes, *J. Power Sources* 195 (2010) 3425–3430, <http://dx.doi.org/10.1016/j.jpowsour.2009.12.022>.
- [26] A. Schenk, C. Grimmer, M. Perchthaler, S. Weinberger, B. Pichler, C. Heinzl, C. Scheu, F.A. Mautner, B. Bitschnau, V. Hacker, Platinum-cobalt catalysts for the oxygen reduction reaction in high temperature proton exchange membrane fuel cells - long term behavior under ex-situ and in-situ conditions, *J. Power Sources* 266 (2014) 313–322, <http://dx.doi.org/10.1016/j.jpowsour.2014.05.023>.
- [27] J. Zhang, H. Li, Effect of operating backpressure on PEM fuel cell performance, *ECS Trans.* 19 (2009) 65–76, <http://dx.doi.org/10.1149/1.3271363>.