**Improved performance of self-reactivated Pt–ThO₂/C catalysts in a direct ethanol fuel cell**

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A novel self-reactivated catalyst Pt–ThO₂/C was prepared for the first time by selecting radioactive material ThO₂ as the catalytic additive to address the low activity and toxicity of the anode Pt/C catalyst in a direct ethanol fuel cell. The catalytic activity and resistance to CO poisoning of Pt–6.67 wt%ThO₂/C were found to be superior to those of Pt/C–NaBH₄ in electrochemical workstation and single-cell tests. It is speculated that the existence of ThO₂ not only improves the catalytic activity via the synergistic effect of Pt and Th, but also produces a large amount of radiolysis products, OH radicals, due to ²³²Th which oxidatively desorbs CO from Pt–CO_ads and solves the CO poisoning problem.

Numerous fundamental studies have been reported that Pt-based catalyst shows the most excellent performance in acidic DEFCs and Nafion membranes, the proton exchange membrane (PEM) are commonly applied. What’s more, the design of multimodal porous carbon for the interfacial microporous layer has also been studied to improve the performance of electrocatalyst. The development of electrocatalysts plays a crucial role in improving the performance of fuel cells. In addition to exploring high-efficient approaches to synthesize catalysts, the factors responsible for superior catalytic activity and stability of nanocatalysts have also been inspected to further conduct the synthesis of electrocatalysts. And the impacts of ligands on the catalytic activities of like PtRu, PtPd and Pt/C have deepen the understanding of the application of heterogeneous catalysis.

However, fabrication or manufacture of Pt/C catalyst is the foremost obstacle to the application and commercialization of DEFC because of its high cost (accounts for 36% of the fuel cell’s total expenditure) and the performance drop attributed by the poor ability to resist CO poisoning. Ethanol in the anode catalytic layer generates CO-intermediates as a result of incomplete oxidation. It has been confirmed by in situ infrared spectroscopy that the intermediate product CO is adsorbed on the Pt surface by linear adsorption, forming stable Pt carbonyl groups (Pt + CO → Pt–CO_ads). As CO covers the active site of Pt, it affects the Pt/C catalytic performance and prevents further dissociation of ethanol, ultimately leading to a dramatic decrease in the overall cell performance.

In addition to scan the poisoned Pt/C electrode in 0.5 mol L⁻¹ H₂SO₄ solution, there are three other ways to settle the catalyst performance drop caused by the CO poisoning: (1) based on the bifunctional mechanism, the addition of some non-Pt elements to the Pt/C catalyst can contribute to the removal of CO. M. Watanabe et al. explained the detoxification...
mechanism of Pt–Ru/C catalysts, where Pt adsorbs the intermediate product CO to form Pt carbonyl groups (Pt + CO → Pt–CO$_{ads}$) and Ru decomposes and adsorbs OH radicals from water at low potentials (Ru + H$_2$O → Ru–OH$_{ads}$ + H$^+$ + e$^-$), which rapidly oxidizes CO on the Pt surface to CO$_2$ for discharge (Pt–CO$_{ads}$ + Ru–OH$_{ads}$ → CO$_2$ + H$^+$ + e$^-$), exposing the Pt active site and restoring the catalytic activity. Yunteng Qu et al. prepared a Pt–SnO$_2$/graphene catalyst and tested the t–i curve, finding out that the resistance to CO poisoning was significantly better than Pt/graphene because the formation of adsorbed oxygen-containing groups OH$_{ads}$ on the SnO$_2$ surface at low potentials could improve the efficiency of CO oxidation. Xiuyi Wang et al. investigated that applying Pt–Au/CNT@TiO$_2$ catalyst prepared by adding TiO$_2$ to Pt–Au/CNT to the system could improve the resistance to poisoning. One reason is that TiO$_2$ increases the electron density of the alloy by interacting with Pt–Au alloy, and some electrons are transferred to the anti-bonding orbital of CO, weakening the bonding strength of the C–O bond while reducing the oxidation overpotential. For another, according to the bifunctional mechanism, the Ti ions in the high valence state decompose water molecules to form OH$_{ads}$ species in the adsorbed state, which oxidize CO on the Pt surface to produce CO$_2$.

There are also Pt–RuO$_2$, Pt–ZrO$_2$ (ref. 37 and 38) and Pt–WO$_3$ (ref. 39 and 40) that improve the catalyst’s resistance to CO poisoning through a bifunctional mechanism. (2) By changing the electronic structure of Pt through the ligand effect, the bond strength between Pt carbonyl groups (Pt–CO$_{ads}$) could be weakened, which is conducive to promoting the oxidative desorption of CO and improving the resistance of the catalyst to poisoning. J. R. Kitchin et al. found through density function theory that Pt–Ti, Pt–V, Pt–Cr, Pt–Mn, Pt–Fe, Pt–Co Pt–Ni bimetals can change the electronic structure of the Pt surface through electronic interactions, also known as the ligand effect, thus changing chemical properties and weakening ability of platinum to adsorb CO.

(3) The introduction of oxygen-containing groups in the catalyst carrier improves the resistance to CO poisoning of the catalyst. Xiaomei Chen et al. prepared the catalyst PtPdNPs/GNs by loading Pt–Pd alloys on graphene nanosheets and prepared catalysts Pd/GNs, PtPdNPs/C for comparison. The 1000 second i–t curves were tested to evaluate the resistance of the catalysts to CO poisoning. At the end of the 1000 second test, the ethanol oxidation current density of PtPdNPs/GNs was still much higher than the other catalysts, so the resistance to CO poisoning was better. One of the reasons for the improved resistance to poisoning is that the authors used the Hummers’ method to prepare graphene oxide, where the carrier introduces a large number of oxygen-containing groups, which are later reduced to graphene as the catalyst carrier, and the remaining oxygen-containing groups on the carrier help to remove CO from the Pt–Pd alloy. The other reason is that, relative to Pt, Pd is proved to be more oxtropic with lower cost, which can act as an oxidation promoter by forming oxygen-containing species on the Pd metal particles, oxidizing and removing CO from the Pt surface.

The natural abundance of $^{232}$Th is almost 100%, with a half-life of $1.4 \times 10^{10}$ years, a thorium valence of +4 corresponding to the oxide ThO$_2$, insoluble in water and alkali while soluble in H$_2$SO$_4$ solution. Lijin Xu et al. mixed SrCO$_3$, BaSO$_4$ and ThO$_2$ powders in a mortar and crushed them into small particles under high pressure, and calcined at 900 °C for 0.5 h to obtain the catalyst. The catalyst was then utilized to catalyze the methane oxidation coupling reaction. During the action of the catalyst, the hydrocarbon bond of methane is broken and the hydrogen is released to interact with oxygen to form water, likewise the C$_2$ double bond (alkene bond) is formed to produce olefins. The addition of ThO$_2$ significantly improves the C$_2$ yield and C$_2$ selectivity relative to SrCO$_3$/BaSO$_4$, since introducing ThO$_2$ substitutes Th$^{4+}$ for Sr$^{2+}$ as well as Ba$^{2+}$, increasing the number of lattice defects and improving the catalytic activity. Ramya Arumugam et al. synthesized ThO$_2$/Fe$_3$O$_4$ nanocomposites by hydrothermal methods with larger specific surface area, more active sites and higher stability for the catalytic and removal of triphenylmethane dyes (MG) from the aqueous phase with a degradation rate about 99.53% at pH = 5. Nanostructured N-doped ThO$_2$ was synthesized by Wei, HT et al. and the material exhibited significant visible light absorption and high photocatalytic activity for the reduction of Cr(vi) under visible light (wavelength >420 nm) irradiation. Co–ThO$_2$–ZSM-5 bifunctional zeolite catalysts were prepared for catalyzing the conversion of carbon monoxide and hydrogen to hydrocarbons by Murty A. N. et al. The catalytic performance (i.e. activity and selectivity) of the composites depended on the content of cobalt on the mesoporous zeolite ZSM-5 and the co-catalytic effect of ThO$_2$. Considering the co-catalytic effect of ThO$_2$ as shown above and the radioactivity property of it, we selected ThO$_2$ to inspect its effect on the Pt/C catalyst.

In this work, we report the catalytic activity, durability, and resistance to CO poisoning of the novel catalyst Pt–ThO$_2$/C in which the catalytic activity of ThO$_2$ was firstly taken into consideration to address the problem of CO poisoning in the anode Pt/C catalyst of DEFC. The catalyst Pt–ThO$_2$/C was synthesized by loading Pt particles onto the ThO$_2$-loaded carbon carrier via impregnation-reduction method and characterized by TEM, EDS, XRD, ICP-MS and XPS. The catalytic performance of the catalyst was tested by an electrochemical workstation and three electrodes. Likewise, Pt–xThO$_2$/C was assembled into a fuel cell to test the maximum cell power density.

**Results and discussion**

**Physical characterization results**

**TEM.** Fig. 1(a) shows the TEM image and the particle distribution of the ThO$_2$ which reveals that ThO$_2$ particles prepared by hydrothermal method have good dispersion and relatively uniform particle size with an average particle size of 3.86 nm. Fig. 1(b–d) show the TEM images and the Pt particle distribution of the Pt-6.67%ThO$_2$/C, Pt-40%ThO$_2$/C and Pt/C–NaBH$_4$. As is indicated in the figure, the distribution of Pt on the carbon carrier is rather agglomerated with uneven dispersion, probably due to the violent reaction of NaBH$_4$ in reducing H$_2$PtCl$_6$. Based on the particle distribution, the average particle sizes are 11.09 nm, 14.15 nm and 12.40 nm in order in which the average particle size of the catalyst is the largest when the...
mass fraction of ThO₂ is 40%. Probably the increased number of particles loaded on the carbon results in poorer dispersion and increased agglomeration.

**EDS.** The EDS analysis of surface distribution as shown in Fig. 2 clarified that both Pt and ThO₂ are successfully loaded on the carbon carrier. What’s more, ThO₂ particles (also the ²³³-Th) are well dispersed on the catalyst.

**XRD.** The XRD patterns of the prepared materials are shown in Fig. 3. Fig. 3(a) is the XRD pattern of ThO₂ prepared by hydrothermal method, the peak positions and relative intensities of the diffraction peaks correspond to the ThO₂ standard PDF card 65-0291. Fig. 3(b) is the XRD pattern of the 11 catalysts, the diffraction peaks at 27° and 31° correspond to the (111) and (200) crystalline planes of ThO₂, and the diffraction peaks at 39° and 46° correspond to the (111) and (200) reflections of Pt. The XRD patterns indicate that ThO₂ and Pt have been loaded onto the carbon. As the loading of ThO₂ increases, the diffraction peaks become stronger and stronger, while the diffraction peaks of Pt basically remain the same except that the peak at 46° becomes sharper indicating the content of (200) reflection increases and the crystalline grain of Pt enlarges. The result of larger crystalline grain of Pt with increased loading of ThO₂ is also consistent with Fig. 1(b) and (c).

**XPS.** As shown in the Fig. 4, the presence of C, Pt, O and Th in the Pt-10 wt%ThO₂/C catalyst are confirmed. The two peak of Th

![Fig. 1](image1)  (a) TEM micrograph and particle size distribution of ThO₂; TEM micrographs and the Pt particle size distribution of the synthesized catalysts (b) Pt-6.67%ThO₂/C, (c) Pt-40%ThO₂/C and (d) Pt/C–NaBH₄, respectively.

![Fig. 2](image2)  Pt–ThO₂/C catalyst surface distribution of Th, Pt, C and O.

![Fig. 3](image3)  X-ray diffraction patterns of (a) ThO₂ and (b) Pt–xThO₂/C.

![Fig. 4](image4)  XPS regions (a) Th 4f½2 and 4f½2, (b) C 1s, (c) O 1s and (d) Pt 4f lines of Pt-10 wt%ThO₂/C.
Table 1  Actual loading value of Pt and ThO₂ in the catalysts

| Catalysts                   | Pt  | ThO₂ |
|-----------------------------|-----|------|
| 20%Pt-40%ThO₂/C            | 18.9%| 36.3%|
| 20%Pt-20%ThO₂/C            | 19.0%| 19.4%|
| 20%Pt-10%ThO₂/C            | 19.3%| 9.9% |
| 20%Pt-6.67%ThO₂/C          | 18.2%| 6.0% |
| 20%Pt-3.33%ThO₂/C          | 20.9%| 3.3% |
| 20%Pt-1.67%ThO₂/C          | 19.5%| 1.5% |
| 20%Pt-0.83%ThO₂/C          | 19.7%| 0.9% |
| 20%Pt-0.42%ThO₂/C          | 19.4%| 0.4% |
| 20%Pt-0.21%ThO₂/C          | 18.9%| 0.1% |
| 20%Pt-0.1%ThO₂/C           | 19.2%| 0.08%|
| 20%Pt/C- NaBH₄             | 19.3%| 0%   |

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H2SO4 and 0.5 mol L\(^{-1}\) C2H5OH at a constant current of 0.1 mA. Within a very short initial period of time, the electrode potential rises sharply to the ethanol oxidation onset potential. As the test time increases, the electrode potential first rises slowly. The intermediate product CO produced during the oxidation of ethanol gradually accumulates on the catalyst surface, making the electrocatalytic activity of the catalyst decrease and the overpotential of ethanol oxidation increase, and in order to meet the set current conditions, the electrode potential must rise accordingly. As the catalyst is further poisoned, the catalyst surface is almost completely covered with toxic species and the electrocatalytic oxidation of ethanol is almost impossible, at which point the electrode potential rises sharply until it reaches the oxygen precipitation potential as a means of meeting the set current demand. The resistance of the catalyst to CO poisoning is evaluated on the basis of the time taken for the electrode potential to rise sharply to a sudden jump. Pt-6.67% ThO2/C shows a potential jump time of 337 s and Pt/C–NaBH4 shows a potential jump time of 60 s, so Pt-6.67% ThO2/C is more resistant to CO poisoning, most likely due to the self-reactivation effect mentioned above.

**Single cell performance**

To further investigate the modification effect of ThO2 on Pt/C catalyst, Pt-6.67% ThO2/C and Pt/C–NaBH4 were used as anode catalyst to assemble single cell and respectively test the cell V–i polarization curves. Fig. 8 shows the V–i polarization curves and power density curves for the two catalysts. The V–i curve is polarized for three main reasons, one is activation polarization, when a chemical reaction occurs on the electrode surface to output current, the reaction resistance must be overcome, the reaction resistance leads to polarization. Secondly, ohmic polarization, when the battery is operated, the flow of ions and electrons will be subject to resistance to produce a voltage drop, and resistance leads to polarization. Third is the concentration difference polarization, if the rate of transport of ethanol to the electrode is less than the rate of consumption, it will cause the concentration of ethanol on the surface of the electrode to be lower than its own concentration, this concentration difference leads to polarization.

Fig. 8 V–i curves also show that the polarization of Pt/C–NaBH4 is more obviously than Pt-6.67% ThO2/C. Moreover, according to the power density curves, it can be found that the

| Catalysts                | 1st ethanol oxidation peak current density mA cm\(^{-2}\) | 200th ethanol oxidation peak current density mA cm\(^{-2}\) |
|--------------------------|------------------------------------------------------|----------------------------------------------------------|
| 20%Pt-40%ThO2/C          | 2.16 (100%)                                          | 1.88 (87.0%)                                             |
| 20%Pt-20%ThO2/C          | 2.36 (100%)                                          | 2.12 (89.8%)                                             |
| 20%Pt-10%ThO2/C          | 2.57 (100%)                                          | 2.34 (91.0%)                                             |
| 20%Pt-6.67%ThO2/C        | 3.38 (100%)                                          | 3.23 (95.5%)                                             |
| 20%Pt-3.33%ThO2/C        | 3.25 (100%)                                          | 3.09 (95.0%)                                             |
| 20%Pt-1.67%ThO2/C        | 3.19 (100%)                                          | 3.11 (97.4%)                                             |
| 20%Pt-0.83%ThO2/C        | 2.82 (100%)                                          | 2.74 (97.1%)                                             |
| 20%Pt-0.42%ThO2/C        | 3.01 (100%)                                          | 2.94 (97.6%)                                             |
| 20%Pt-0.21%ThO2/C        | 2.64 (100%)                                          | 2.58 (97.7%)                                             |
| 20%Pt-0.1%ThO2/C         | 2.40 (100%)                                          | 2.29 (95.4%)                                             |
| 20%Pt/C–NaBH4            | 2.34 (100%)                                          | 2.17 (92.7%)                                             |
maximum power density of single cell is 20.52 mW cm$^{-2}$ for Pt-6.67%ThO$_2$/C and 18.96 mW cm$^{-2}$ for Pt/C–NaBH$_4$. So it is further clear from the fuel cell test results that the addition of ThO$_2$ can improve Pt/C catalytic performance.

**Experimental**

**Materials**

Cabot carbon (XC-72) was purchased from Suzhou Xinero. Th(NO$_3$)$_2$.4H$_2$O (AR) was purchased from Changsha Jingkang. H$_2$PtCl$_6$.6H$_2$O (AR), Na$_2$C$_6$H$_5$O$_7$.2H$_2$O (AR), C$_2$H$_5$OH (GR), NaBH$_4$ (AR) were purchased from Aladdin reagent. NaOH (AR) and H$_2$SO$_4$ (AR) were purchased from sinopharm chemical reagent. C$_2$H$_5$OH (AR) was purchased from Macklin reagent. Nafton (5 wt%) was purchased from Shanghai Hesen.

**Synthesis of Pt–ThO$_2$/C catalysts**

Procedure for synthesis of ThO$_2$. 5 mL of 0.8 mol L$^{-1}$ Th(NO$_3$)$_2$.4H$_2$O solution was added dropwise to 75 mL of 6.4 mol L$^{-1}$ NaOH (aq) and the mixed solution was stirred at room temperature for 30 min. The mixed solution was then transferred into a 100 mL Teflon lined stainless steel reactor with hydrothermal treatment at 100 °C for 24 h. After the reactor had cooled to room temperature, the material was washed with ultrapure water and dried to obtain the white powder of ThO$_2$.

Procedure for synthesis of Pt–xThO$_2$/C catalysts. Weigh 146 mg of carbon into a round bottom flask, add 50 mL of ultrapure water and 25 mL of C$_3$H$_8$O into the flask, sonicate for 20 min, stir for 10 min, then adjust the solution pH > 10 with 0.1 mol L$^{-1}$ NaOH. 14 mg of homemade Th$_2$O$_3$ was added into 5 mL of ultrapure water, sonicate and disperse, then pour into the flask and stir for 10 min. Subsequently, a solution of H$_2$PtCl$_6$.6H$_2$O containing 42 mg Pt and 13 mg Na$_2$C$_6$H$_5$O$_7$.2H$_2$O was added in the flask. After stirring for 20 min the flask was transferred to a water bath at 80 °C and stirred for 2 h, during which time an excess of NaBH$_4$ solution was added dropwise to the flask. Finally, the material was washed by centrifugation using ultrapure water, dried overnight at 60 °C and ground to obtain the catalyst, noted as Pt-6.67%ThO$_2$/C. Note that the percentages mentioned about ThO$_2$ are all mass fraction in this article. The same process was used to prepare other Pt–xThO$_2$/C ($x = 40, 20, 10, 3.33, 1.67, 0.83, 0.42, 0.21$ and $0.1%)$ as well as Pt/C–NaBH$_4$ with a stable Pt loading of 20 wt% in all catalysts.

**Physical characterizations**

The microstructure of Pt–xThO$_2$/C Pt–xThO$_2$/C and Pt/C–NaBH$_4$ was observed by the transmission electron microscopy (TEM) measurement with JEM-F200 manufactured by Japan Electronics Corporation. The sample was prepared by sonicating the material into anhydrous ethanol and then adding a small amount of the suspension drop by drop onto a copper grid to dry for measurement.

Energy dispersive spectroscopy (EDS) tests were carried up on a SU8020 manufactured in Hitachi of Japan to roughly observe the existence and distribution of the elements on the surface of the catalyst Pt–xThO$_2$/C.

The physical phases present in the material was characterized by the X-ray diffraction technique (XRD) on a Bruker D8 ADVANCE, manufactured in Germany, equipped with a Cu-Kz X-ray source and operated at a voltage of 40 kV, a current of 40 mA and a test angle of 5–90°.

The X-ray photoelectron spectroscopy (XPS) was obtained on a VG Multilab 2000 using Al Kz (1486.7 eV) as the exciting radiation to further confirm the presence and the chemical states of the elements at the materials’ surface.

Inductively coupled plasma mass spectrometer (ICP-MS) measurements were conducted on an Agilent 7850 ICP-MS from Agilen of Japan to analyze the elemental content of the solution.

**Electrochemical measurements**

An electrochemical workstation with a three-electrode system was used to test the catalytic performance of the catalysts. The electrochemical workstation used for the experiments was manufactured by Shanghai Chenhua, model CHI760E. The three electrodes are, in order, a saturated calomel electrode as reference electrode, model CHI150, with a saturated KCl solution inside the saturated calomel electrode; a platinum wire electrode as counter electrode, model CHI115; and a glassy carbon electrode as working electrode, model CHI104, with a 3 mm diameter glassy carbon in the middle part of the glassy carbon electrode. All three electrodes were purchased from Shanghai Chenhua. When the electrochemical workstation is in operation, the three electrodes form two circuits, where the working electrode loaded with catalyst and the reference electrode form a circuit to test the working electrode potential, as the reference electrode potential is known to be constant. For example, the standard electrode potential of a saturated calomel electrode is 0.2412 V. The potential output from the workstation is the difference in potential between the working and reference electrodes. The working electrode and counter electrode form a circuit to test the working electrode current, this is known as the “three electrodes and two circuits”. The

![Fig. 8](image-url)
working electrode is prepared as follows: using in turn 0.3 μm and 0.05 μm Al₂O₃ powder, the electrode is polished on a polishing flannel with the aim of polishing the glassy carbon to a mirror-like surface without scratches and the PTFE material wrapped around the glassy carbon to a very hydrophobic surface. Weigh 10 mg of the catalyst to be tested, add to 2.4 mL of ultra-pure water, 0.1 mL of Nafion, 2.5 mL of C₂H₅OH and sonicate for 30 min to obtain a 2 mg mL⁻¹ slurry of catalyst. Pipette 5 μL of the slurry onto the glassy carbon electrode and allow drying naturally as a working electrode.

**Fuel cell measurements**

The catalyst to be tested was ultrasonically dispersed with the Nafion solution in C₂H₅OH under ice bath conditions. The catalyst suspension was then sprayed onto a PTFE film as the catalytic layer and subsequently hot-pressed onto both sides of a Nafion 115 film at 120 °C and 10 MPa maintained for 120 s. The outermost side used carbon cloth (H2315T10AC1 NOK, Japan) as the diffusion layer to form a membrane electrode (MEA) with an effective area of 2 × 2.5 cm². A homemade catalyst with a Pt loading of 1.2 mg cm⁻² was used for the cell anode and a commercial Pt/C with a Pt loading of 1.2 mg cm⁻² was used for the cathode, with a Nafion solution (5 wt%) content of 15 wt% for the anode and 10 wt% for the cathode. The cell operating temperature was set at 60 °C with 2 mol L⁻¹ C₂H₅OH passing through the anode at a flow rate of 1.5 sccm and O₂ passing through the cathode at a flow rate of 400 sccm. Prior to testing, a 0.5 mol L⁻¹ H₂SO₄ solution was passed from the anode for 30 min at 55 °C for reducing the internal resistance of the proton exchange membrane. The test was then started after passing 0.5 sccm of 1.5 mol L⁻¹ C₂H₅OH solution on the anode side and 800 sccm of O₂ on the cathode and discharging at 100 mA cm⁻² for 10 hours for stabilizing the internal mass transfer channels of the catalytic layer.

**Conclusions**

To settle the low activity and susceptibility to CO poisoning of Pt/C anode catalysts for DEFC, a radioactive ThO₂ catalytic additive prepared by hydrothermal method was introduced into the Pt/C catalyst at first time. TEM, EDS, XRD, XPS and ICP-MS characterization revealed that Pt and ThO₂ were successfully loaded on the carbon carrier and evenly distributed, while the Pt particles were poorly dispersed on the carbon and showed significant agglomeration due to the relatively rapid and violent reaction of NaBH₄ in reducing H₂PtCl₆.

The catalyst performance was determined by electrochemical workstation equipped with three electrodes. It was illustrated by the results that the catalysts prepared with 20% mass fraction of Pt and 6.67% mass fraction of ThO₂ showed the best catalytic activity and resistance to CO poisoning which was significantly improved the performance compared to Pt/C–NaBH₄. The increases mentioned above are partly due to the synergistic effect of Pt and Th. Moreover, Pt–xThO₂/C is a self-reactivated catalyst, i.e., α particles released by the radioactive ²³²Th irradiate water to produce a large amount of strongly oxidizing hydroxyl radicals, which oxidize the CO adsorbed on Pt surface, expose the active site of Pt and promote further dissociation of ethanol. The results of the single cell operating performance of Pt–6.67%ThO₂/C and Pt/C–NaBH₄ used as anode catalysts in DEFC respectively illustrated that the cell polarization was much more severe for Pt/C–NaBH₄, and the maximum power density of the cell was higher for Pt–6.67% ThO₂/C than that of Pt/C–NaBH₄, further confirming the impressive self-reactivation effect of ThO₂ on Pt/C catalyst.

**Author contributions**

Yubing Xue: formal analysis, investigation, visualization, writing – original draft. Dashu Pan: formal analysis, validation. Feng Zuo: data curation, investigation. Songtao Xiao: methodology, project administration. Xiang Li: formal analysis. Fuyan Lou: resources. Mingming Li: writing – review & editing. Yinggen Ouyang: funding acquisition, conceptualization, supervision.

**Conflicts of interest**

There are no conflicts to declare.

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