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Article

An electrode with Ni(II) loaded analcime zeolite catalyst for the electrooxidation of methanol

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ABSTRACT

There is a high overvoltage in the oxidation of methanol in fuel cells, and so modified electrodes are used to decrease it. A modified electrode that used Ni(II) loaded analcime zeolite to catalyze the electrooxidation of methanol in alkaline solution was proposed. Analcime zeolite was synthesized by hydrothermal synthesis, and Ni(II) ions were incorporated into the analcime structure, which was then mixed with carbon paste to prepare modified electrode. The electrocatalytic oxidation of methanol on the surface of the modified electrode in alkaline solution was investigated by cyclic voltammetry and chronoamperometry. The effects of the scan rate of the potential, concentration of methanol, and amount of zeolite were investigated. The rate constant for the catalytic reaction of methanol was $6 \times 10^3 \text{ cm}^3 \text{ mol}^{-1} \text{ s}^{-1}$ from measurements using chronoamperometry. The proposed electrode significantly improved the electron transfer rate and decreased the overpotential for methanol oxidation.

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1. Introduction

Direct methanol fuel cells (DMFCs) have several advantages over other fuel cells such as high efficiency, very low polluting emission, renewable fuel source, and fast and convenient refueling [1]. Also, methanol as the fuel has many advantages such as simple operation, ease of storage, high energy density, and low price [2], but the relatively slow kinetics of the methanol oxidation reaction (MOR) leads to high overpotentials [3]. So, there is much interest in developing new materials for the electrocatalysis of the MOR in alkaline medium. The use of alkaline solutions in a fuel cell has many advantages such as increasing its efficiency [4,5], a wider selection of possible electrode materials, higher efficiency of both anodic and cathodic processes, almost no sensitivity to the surface structure, and negligible poisoning [6,7].

One way to decrease the high overvoltage of the MOR is to use zeolites to modify the electrode. Zeolite-modified electrodes (ZMEs) have several advantages arising from their unique size, shape, and selectivity together with high ion exchange capacity [8]. Zeolites are aluminosilicate crystalline materials, which have intricate pores and channels that are occupied by large cations and water molecules. They are widely used as adsorbents, ion exchangers, catalysts, and catalyst supports [9–12].

Analcime (ANA) zeolite has a structure built of TO_4 ($\text{T} = \text{Al}, \text{Si}$) tetrahedral with each corner oxygen being shared by two tetrahedrons, and its small pores have four, six, and eight ring openings [13]. Small pore zeolites such as ANA are important for applications such as selective adsorption and heterogeneous catalysis. The small pores of analcime make it a good adsorbent for the extraction of trace metal ions such as palladium,

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copper, and nickel from water and synthesis samples [14–16]. The catalytic activity and other properties of zeolites can be improved by the incorporation of metal ions or organic ligands into the structure of these materials by a cation exchange process [17–20]. These characteristics of zeolites together with their low cost and resistance to various chemical environments have made them useful for analytical applications [21].

Afzali et al. [22] used ANA zeolite modified with 2-(5-bromo-2-pyridylazo)-5-diethylaminophenol (5-Br-PADAP) for the pre-concentration and anodic stripping voltammetric determination of trace amounts of cadmium. Also, the separation and pre-concentration of trace amounts of copper ion in aqueous solution was achieved by the selective and quantitative adsorption of it during the passage of an aqueous solution through a tetradecyldimethylbenzylammonium chloride (TDMBAC)-treated analcime with the pyrocatechol immobilized [15].

Transition metal ion exchanged zeolites such as Fe-zeolite [23–25], Ni-zeolite [26–28], and Cu-zeolite [29–31] have high catalytic activities and are appropriate for catalytic purposes. The modification of ANA with metal ions such as Ni^{2+} and Cu^{2+} provides a good catalyst for the oxidation of organic materials. In our previous work, we synthesized Cu-modified ANA and investigated its activity in the oxidation of benzyl alcohol [32]. Here we investigate the catalytic performance of modified ANA in the methanol oxidation reaction. Although metals such as Pt and Pt-Ru are very active in the anodic oxidation of methanol, they are too expensive for practical applications. By the incorporation of some other active metal ions such as Ni, we can prepare an inexpensive catalyst for methanol oxidation. One of the very important uses of Ni is as a catalyst for the oxidation of alcohols [33,34]. In this work, Ni-loaded ANA (Ni/ANA) was synthesized. It was used as the modifier in the preparation of a modified carbon paste electrode (Ni/ANACPE) to investigate its use in the catalysis of the electrooxidation of methanol in alkaline medium.

2. Experimental

2.1. Synthesis of zeolite

ANA was synthesized by a method previously reported [35]. Briefly, silicic acid was dissolved in sodium hydroxide solution at 60 °C for 30 min, and aluminum powder was dissolved in (3.7 mol/L) sodium hydroxide solution to obtain the aluminate solution. Then, the aluminate solution was added to the silicic acid solution, and the mixture was stirred to produce a gel. Finally, the gel was transferred into a Teflon-lined stainless steel autoclave and heated for five days at 160 °C. The precipitate was recovered by filtration, washed with deionized water, and dried at 80 °C.

2.2. Electrode preparation

ANA (0.3 g) was dispersed in 15 mL of 1 mol/L nickel chloride solution and stirred at room temperature for 24 h. Then, Ni/ANA (the cation exchanged zeolite) was filtered and washed with deionized water several times and dried in an oven at 70

°C for 8 h. Afterwards, a mixture of 0.3 g Ni/ANA, 0.7 g graphite powder, and an appropriate amount of paraffin was blended by hand mixing with a mortar and pestle for the preparation of the zeolite-modified carbon paste (ZMCP). A portion of the prepared paste was packed into the end of a glass tube (internal radius 1.5 mm). Electrical connection was implemented by a copper wire lead fitted into the glass tube. Finally, the modified electrode was immersed in 1 mol/L Ni(II) solution for 10 min. Then, the modified electrode (Ni/ANACPE) was washed with deionized water to remove adsorbed species.

In order to investigate the electrocatalytic behavior of Ni/ANACPE in the oxidation of methanol, CPE and Ni/CPE were prepared for blank experiments. CPE was prepared in the same way but without the Ni/ANA. Ni/CPE was prepared by soaking CPE in 1 mol/L Ni(II) solution for 10 min. In order to clarify the role of ANA in the oxidation of methanol, ANACPE was prepared by adding non-modified ANA to CPE.

2.3. Apparatus and chemicals

X-ray diffraction (XRD) patterns were recorded with an X-ray diffractometer (Shimadzu XD-DL) using $\text{Cu-K}\alpha$ radiation ($\lambda = 1.5418 \text{ \AA}$) at 35.4 kV and 28 mA with a scanning speed of $2\theta = 10^\circ/\text{min}$. Fourier transform infrared (FT-IR) spectra were recorded with an FT-IR spectrometer (Tensor 27-Bruker) at room temperature in the range of 400–4000 cm^{-1} . Field emission scanning electron microscopy (FE-SEM, HITACHI, S-4160) was used to determine the crystallite size and morphology of the samples.

All electrochemical experiments were performed using a Dropsens Bipotentiostat/Galvanostat ($\mu\text{STAT 400}$). A Ag|AgCl|KCl (3 mol/L) (Azar Electrode Co., Iran) electrode, a platinum wire, and Ni/ANACPE were used as the reference, auxiliary, and working electrodes, respectively. Silicic acid, aluminum powder, sodium hydroxide, graphite powder, nickel chloride, and methanol were purchased from Merck.

3. Results and discussion

3.1. Characterization of the synthesized ANA

Figure 1 shows the XRD pattern of the synthesized sample. By comparison of the main peaks at $2\theta = 15.92^\circ$, 26.06° , and

Fig. 1. XRD pattern of the synthesized ANA.

Fig. 2. FT-IR spectrum of ANA.

30.65° with those of the reference sample [36], the crystallization of a pure ANA phase was confirmed.

The FT-IR spectrum of the sample showed all the characteristic bands of ANA (Fig. 2). The absorption band at 451 cm⁻¹ is the bending vibration of tetrahedral T-O (T = Si, Al) bonds, and the band at 744 cm⁻¹ was assigned to the symmetric stretching vibration of the T-O bonds. The asymmetric stretching vibration of the tetrahedral T-O bonds has a band at 1014 cm⁻¹, and the bending H-O-H vibration has a band at 1637 cm⁻¹. The broad absorption band at 3500 cm⁻¹ was due to the stretching vibrations of O-H groups [37].

The SEM micrograph of the synthesized ANA is displayed in Fig. 3, which shows the formation of crystallites with an icositetrahedron morphology and an average particle size of 10 μm.

3.2. Electrochemical behavior of Ni/ANACPE

When Ni/ANACPE was placed in an electrolyte solution (0.1 mol/L NaOH), ion exchange occurs between the intra-zeolite Ni(II) ions and the electrolyte cations (Na⁺). As a result of this ion exchange, Ni(II) ions were transported to the surface of the electrode where they were active for the electrocatalytic oxidation of methanol [38]. At the ANA/electrolyte interface, Ni(II) ions were converted to Ni(OH)₂ species by reaction with hydroxide ions.

Figure 4 shows the electrochemical response of CPE and Ni/ANACPE in the absence and presence of 0.02 mol/L methanol in 0.1 mol/L NaOH recorded at a potential sweep rate of 20 mV/s. As can be seen in Fig. 4(a), in the absence and presence

Fig. 3. SEM image of synthesized ANA crystals.

Fig. 4. Cyclic voltammograms of CPE (a) and Ni/SBACPE (b) in the absence (1) and presence (2) of 0.02 mol/L methanol in 0.1 mol/L NaOH at a scan rate of 20 mV/s.

of methanol, no peak was observed in the voltammogram of CPE. However, a pair of redox peaks with an anodic peak potential (E_{pa}) of 0.5 V and a cathodic peak potential (E_{pc}) of 0.36 V were observed with Ni/ANACPE in 0.1 mol/L NaOH (Fig. 4(b-1)). The appearance of the redox peaks was due to the oxidation of Ni(OH)₂ to nickel oxy-hydroxide (NiOOH) in the anodic sweep and reduction of the nickel oxy-hydroxide to Ni(OH)₂ in the cathodic sweep. The redox behavior of Ni/ANACPE can be written as

In the presence of 0.02 mol/L methanol, an increase in the anodic peak current was observed as a result of the oxidation of methanol on Ni/ANACPE (Fig. 4(b-2)).

The effect of scan rate on the electrochemical behavior of Ni/ANACPE was investigated in 0.1 mol/L NaOH. As can be seen in Fig. 5(a), a pair of redox peaks with $E_{1/2} = 431$ mV and the peak-to-peak potential separation (ΔE_p) of 112 mV appeared at the scan rate of 10 mV/s. This was attributed to the limitation of the charge transfer kinetics due to chemical interactions between the electrolyte ions and modified film. This interpretation used Laviron's theory for the linear potential sweep voltammetric response when surface confined electroactive species were present at low concentrations [39]. The following expressions can be written for the peak-to-peak separation of $\Delta E_p > 0.2/n$ V, where n is the number of exchanged electrons:

$$E_{pa} = E^0 + X \ln((1-\alpha)/m) \quad (2)$$

$$E_{pc} = E^0 + Y \ln(\alpha/m) \quad (3)$$

$$\log k_s = \alpha \log(1-\alpha) + (1-\alpha) \log \alpha - \log(RT/(nFv)) - \alpha(1-\alpha)nF\Delta E_p/(2.303RT) \quad (4)$$

$X = RT/(1-\alpha)nF$, $Y = RT/\alpha nF$, and $m = (RT/F)(k_s/nv)$. E_{pa} and E_{pc} are the anodic and cathodic peak potentials, respectively, and α , k_s , and v are the electron transfer coefficient, apparent charge transfer rate constant, and scan rate, respectively. α can be determined from the variation of the peak potential with respect to the scan rate, and k_s can be obtained from the electron transfer rate between the electrode and the surface-deposited layer by measuring the E_p values. From the cyclic voltammograms in Fig. 5(a), the plot of E_p versus $\log v$ was

Fig. 5. (a) Cyclic voltammograms recorded for Ni/ANACPE in 0.1 mol/L NaOH at scan rates of (1) 0.005, (2) 0.01, (3) 0.02, (4) 0.025, (5) 0.035, (6) 0.05, (7) 0.06, (8) 0.08, (9) 0.1, (10) 0.2, (11) 0.3, (12) 0.4, (13) 0.6, (14) 0.7, and (15) 0.8 V/s; (b) Plot of E_p vs $\log v$ of the cyclic voltammograms for the anodic peaks (1) and cathodic peaks (2); (c) The dependency of I_{pa} and I_{pc} on lower values of v (0.005–0.06 V/s); (d) The dependency of I_{pa} and I_{pc} on $v^{1/2}$ at higher values of v ($v > 0.06$ V/s).

obtained in the ranges of 0.005–0.6 V/s for both anodic and cathodic peaks (Fig. 5(b)). It can be seen that E_p was proportional to $\log v$ at $v > 0.06$ V/s, which agreed with Laviron's theory. From Fig. 5(b) and using Eqs. (4) and (6), the values of the anodic (α) and cathodic (β) electron transfer coefficients were 0.7 and 0.3, respectively. From these values, it can be deduced that the rate limiting steps for the anodic and cathodic processes were not the same [40]. By using Eq. (3) for the scan rate of 300 mV/s, the mean value of k_s was calculated to be 0.69 s⁻¹.

As can be seen in Fig. 5(c), there was a linear dependence between the anodic and cathodic peak currents with scan rates at low values from 0.005 to 0.06 V/s. This dependence can be attributed to the electrochemical activity of the immobilized redox species on the surface of the modified electrode. From the slope of these lines, the electrode surface coverage (Γ^*) can be calculated using the following equation, which is for the reversible process with the adsorbed species [41]:

$$I_p = n^2 F^2 A v \Gamma^* / (4RT) \quad (5)$$

where I_p , A , and Γ^* stand for peak current, electrode surface area, and the surface coverage of the redox species, respectively.

The total surface coverage of the immobilized active species was calculated as 5.52×10^{-8} mol/cm² from the average of both

the cathode and anode currents. The dependence of the anodic and cathodic peak currents on $v^{1/2}$ for scan rates faster than 0.06 V/s represents a diffusion controlled process in the total redox behavior of the Ni/ANACPE electrode (Fig. 5(d)). This diffusion limiting process occurred as a result of the charge neutralization of the film during the redox process [42,43].

The effect of different ratios of Ni/ANA (20%, 30%, and 40% (w/w)) on the voltammetric responses of the modified electrode was examined by cyclic voltammetry. The results showed that the optimum ratio of Ni/ANA in the modified electrode was 30%. Larger and smaller amounts of the modifier reduced the sensitivity of the electrode response. Larger amounts of the modifier increased the resistance of the electrode and at smaller amounts of the modifier, the number of available NiOOH active site was decreased because of the reduction of available pores for Ni²⁺ insertion.

In order to clarify the role of the modified electrode in the oxidation of methanol, cyclic voltammograms of CPE, Ni/CPE, ANACPE, and Ni/ANACPE were recorded in the solution containing 0.02 mol/L methanol in 0.1 mol/L NaOH (Fig. 6). By comparing Fig. 6(3) with Fig. 6(4), it can be found that ANA has no significant role in the oxidation of methanol. As shown in Fig. 6(2), a small oxidation peak was present at 0.65 V on

Fig. 6. Cyclic voltammograms recorded on CPE (1), Ni/CPE (2), ANACPE (3), and Ni/ANACPE (4) in the presence of 0.02 mol/L methanol in 0.1 mol/L NaOH at scan rate of 20 mV/s.

Ni/CPE. This observation showed that the presence of adsorbed Ni^{2+} ions in CPE was necessary for methanol oxidation. An increase in the anodic oxidation current was only observed on Ni/ANACPE. The increase of oxidation current on Ni/ANACPE was due to the presence of ANA, which has a porous structure, in Ni/ANACPE, which provided a high surface area for NiOOH (electroactive site) formation. As a result, in comparison to Ni/CPE, the amount of electroactive sites for methanol oxidation increased.

Figure 7(a) shows the effect of the concentration of methanol on the redox behavior of Ni/ANACPE. As can be seen in Fig. 7(b), two anodic peaks appeared at low concentrations of methanol. The first anodic peak (p_1) at 0.51 V was related to $\alpha\text{-Ni(OH)}_2/\text{NiOOH}$ conversion, and the second peak at 0.67 V (p_2) was related to the $\beta\text{-Ni(OH)}_2/\text{NiOOH}$ redox process [44]. Ni(OH)_2 has two different crystallographic forms, $\alpha\text{-Ni(OH)}_2$, which is unstable, and $\beta\text{-Ni(OH)}_2$, which is more resistant to oxidation. The α -form is produced in the first stage of the electro-oxidation of the Ni electrode, and during further cycling it is

converted to the β -form [45]. Due to the difference between the redox potentials of $\alpha\text{-Ni(OH)}_2/\text{NiOOH}$ and $\beta\text{-Ni(OH)}_2/\text{NiOOH}$ [46], $\alpha\text{-Ni(OH)}_2$ is converted to NiOOH at a lower potential than $\beta\text{-Ni(OH)}_2$. NiOOH is generated from the oxidation of $\alpha\text{-Ni(OH)}_2$ during the first anodic process (peak p_1), then it is reduced to $\beta\text{-Ni(OH)}_2$ by methanol as the reducing agent [47–50]:

In the above equation P_{ox} refers to methanol oxidation products such as species containing carbonate, formaldehyde, and formate [51,52]. Fleischmann et al. [34] proposed a general mechanism for the oxidation of primary alcohols:

By increasing the potential, the generated $\beta\text{-Ni(OH)}_2$ is converted to NiOOH in alkaline solution, and this leads to the appearance of the peak p_2 at higher potentials according to the following reaction:

The current of both the anodic peak p_1 (assigned to $\alpha\text{-Ni(OH)}_2/\text{NiOOH}$) and p_2 (assigned to $\beta\text{-Ni(OH)}_2/\text{NiOOH}$) increased in the anodic direction at higher concentrations of methanol while the current of the cathodic peak (assigned to NiOOH reduction) decreased in the cathodic direction sweep. A higher concentration of methanol causes more conversion of NiOOH to Ni(OH)_2 by methanol oxidation. This leads to a bigger current because there are more $\beta\text{-Ni(OH)}_2$ species for oxidation.

Figure 8(a) shows cyclic voltammograms of Ni/ANACPE in the presence of 0.02 mol/L methanol in 0.1 mol/L NaOH at various scan rates. As shown in the figure, the anodic peak current increased as a result of increasing the scan rate. As can be seen in Fig. 8(b), two anodic peaks (p_1 and p_2) appeared at low scan rates, but with increasing scan rate, the peak p_2 decreased, and at scan rates faster than 0.2 V/s it disappeared. This observation was due to that at high scan rates, the oxidation of $\beta\text{-Ni(OH)}_2$ to NiOOH was not fast enough to transfer electrons

Fig. 7. (a) Current-potential curves from Ni/ANACPE in the electrocatalytic oxidation of methanol at the scan rate of 20 mV/s in 0.1 mol/L NaOH solution with concentrations of methanol of (1) 0.0, (2) 0.02, (3) 0.04, (4) 0.06, (5) 0.1, (6) 0.2, and (7) 0.35 mol/L, respectively. (b) Zoomed cyclic voltammograms of (2), (3), and (6) from the main panel of (a).

Fig. 8. (a) Cyclic voltammograms of the Ni/ANACPE in the presence of 0.02 mol/L methanol in 0.1 mol/L NaOH, at scan rates of (1) 20, (2) 35, (3) 50, (4) 75, (5) 100, (6) 200, (7) 300, (8) 400, (9) 500, (10) 600, (11) 700, and (12) 800 mV/s, respectively. (b) Zoomed cyclic voltammograms of (1), (4), and (6) from the main panel of (a).

to the electrode while the oxidation of α -Ni(OH)₂ to NiOOH has fast electron transfer kinetics and the anodic current was mainly due to this reaction.

3.3. Chronoamperometric study

The catalytic rate constant of methanol oxidation on Ni/ANACPE was evaluated by chronoamperometry. Double step chronoamperograms of the redox process were recorded by setting the working electrode potential at 700 mV (in first step) and 350 mV (in second step) vs Ag|AgCl|KCl (3 mol/L) at different concentrations of methanol (Fig. 9(a)). From the exponential behavior of the current-time profiles, it can be seen that the process was diffusion-controlled and it can be modeled using the Cottrell equation [41]. Figure 9(b) shows that there was a linear dependence between I and $t^{-1/2}$ in the absence of methanol. The rate constant for the chemical reaction between methanol and the redox sites of Ni/ANACPE was evaluated by

the equation [53]:

$$I_c/I_L = \gamma^{1/2} [\pi^{1/2} \text{erf}(\gamma^{1/2}) + \exp(-\gamma) \gamma^{1/2}] \quad (11)$$

where I_c is the catalytic current of methanol at Ni/ANACPE, I_L is the limited current in the absence of methanol, and $\gamma = kC_0t$ is the argument of the error function (C_0 is the bulk concentration of methanol). If γ exceeds 2, the error function is almost equal to 1 and the above equation can be simplified to

$$I_c/I_L = \gamma^{1/2} \pi^{1/2} = \pi^{1/2} (kC_0t)^{1/2} \quad (12)$$

where k , C_0 , and t are the catalytic rate constant ($\text{cm}^3 \text{mol}^{-1} \text{s}^{-1}$), methanol bulk concentration (mol/L), and time (s), respectively. The catalytic rate constant can be calculated from the slope of the I_c/I_L vs $t^{1/2}$ plot. This plot was obtained from the chronoamperogram of Ni/ANACPE in the absence and presence of 0.02 mol/L methanol in 0.1 mol/L NaOH (Fig. 9(c)). The mean value of k was found to be $6 \times 10^3 \text{ cm}^3 \text{mol}^{-1} \text{s}^{-1}$. The results proved that Ni/ANACPE has good catalytic activity for methanol oxidation.

Table 1 shows the peak potential and peak current density

Fig. 9. (a) Chronoamperometric curves obtained from Ni/ANACPE (1) in the absence and presence of (2) 0.02, (3) 0.1, and (4) 0.2 mol/L methanol in 0.1 mol/L NaOH solution. First and second potential steps were 0.7 and 0.350 V vs Ag|AgCl (KCl 3 mol/L), respectively. (b) Dependence of current on $t^{-1/2}$ derived from the data in the chronoamperogram (1). (c) Dependence of I_c/I_L on $t^{1/2}$ derived from the data of the chronoamperograms.

Table 1

Comparison of the current density and oxidation potential of some nickel modified electrodes used in the electrocatalytic oxidation of methanol in alkaline medium.

Electrode	Modifier	$J/(mA/cm^2)$	E/V	Ref.
Poly-TCPP ^a /Ni	Ni	~6.3	~0.78 vs SCE	[54]
Ni/POAP ^b /MCPE	Ni	~9.91	~0.67 vs Ag/AgCl	[55]
Ni/SBACPE	Ni	~14.2	~0.8 vs Ag/AgCl	[27]
Ni/P-1,5-DAN ^c /MCP	Ni	~1.54	~0.65 vs Ag/AgCl	[56]
GC/NiMn	NiMn	~33.3	~0.62 vs Ag/AgCl	[57]
Ni/ZSMCPE	Ni	~9.2	~0.72 vs Ag/AgCl	[26]
Ni/ANACPE	Ni	~9.0	~0.75 vs Ag/AgCl	this work

^aTetra carboxyphenyl porphyrinato.

^bPoly aminophenol.

^cDiaminonaphthalene.

of methanol electrooxidation on Ni/ANACPE and a comparison with some of the modified electrodes reported in the literature. To measure these values, the current density of Ni/ANACPE in 0.1 mol/L NaOH was subtracted from the total current density obtained in the presence of methanol. The values in Table 1 are for the current density of just methanol oxidation.

By comparing the values in Table 1 it can be concluded that Ni/ANACPE has good catalytic performance in methanol oxidation and is a good candidate for further investigation.

4. Conclusions

ANA was loaded with Ni by dispersion in 1 mol/L nickel chloride solution. The Ni-loaded zeolite was mixed with carbon paste to prepare a modified electrode (Ni/ANACPE). Ni/ANACPE was used to catalyze the electrocatalytic oxidation of methanol in alkaline solution, and the results were investigated by cyclic voltammetry and chronoamperometry. The cyclic voltammograms showed that Ni/ANACPE increased the oxidation current of methanol as compared to CPE and Ni/CPE. With the ANACPE electrode and in the presence of methanol, no peak was observed during the anodic scan, which showed that ANA has no role in the oxidation of methanol because it is a nonconductive material. The porous structure of ANA provides

a framework for Ni²⁺ uptake, which is converted to Ni(OH)₂ and NiOOH during the anodic oxidation in alkaline solution. The Ni-loaded zeolite was active in the electrocatalytic oxidation of methanol. The catalytic rate constant was obtained from the chronoamperograms. The results showed that the modified electrode increased the kinetics of methanol oxidation by a catalytic process and reduced the overpotential of the reaction in alkaline medium.

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Graphical Abstract

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Ni loaded analcime zeolite was used as the catalyst for the electrochemical oxidation of methanol.

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