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STUDY ON ELECTROCHEMICAL PERFORMANCE OF DIMENSIONALLY STABLE ANODES DURING ZINC ELECTROWINNING

In zinc electrowinning, small amounts of manganese ions additives are needed in the electrolyte to reduce the corrosion of anodes and minimize the contamination of cathodic zinc by dissolved lead. However, excess manganese oxide could cover the dimensionally stable anodes (DSA) surface and decrease their service life. Additives of phosphoric acid are put in the electrolyte to complex the manganic Mn^{3+} ion and hence reduce its disproportionation to MnO_2 . In the investigation, phosphoric acid was added to sulfuric acid or zinc electrolytes, and conventional and recent electrochemical measurements were carried out to examine electrochemical behaviour of DSA ($Ti/IrO_2-Ta_2O_5$) anode during zinc electrolysis at 48 mA/cm^2 and 39°C . It was observed that the anodic potentials of DSA anodes were lower by 27 mV after 5 h polarization in the zinc electrolyte containing 35 g/L phosphoric acid at 39°C . Electrochemical impedance measurements show that the addition of 35 ml/L H_3PO_4 to the zinc electrolyte can increase impedance resistances of the DSA mesh anodes. Cyclic voltammogram studies (CV) at a scan rate of 5 mV/s without agitation show that the oxidation peak in the solution with 35 ml/L phosphoric acid addition is highest, followed by that with 17 ml/L phosphoric acid addition and that without addition of phosphoric acid.

Keywords: Zinc electrowinning; Dimensionally stable anodes; Manganese ions; Phosphoric acid; electrochemical performance

1. Introduction

The traditional anodes of choice in the zinc electrowinning industry have been lead based alloys. However, these anodes display much energy consumption and high corrosion resistance during electrolysis. Also, the lead impurity will contaminate the zinc deposit [1]. To solve the problems, other anode materials such as dimensionally stable anodes (DSA), consisting of mixed metal oxide coatings on titanium or nickel substrates, have been investigated. Coating $IrO_2-Ta_2O_5$ on the surfaces of titanium base anodes is used in the zinc sulfuric acid electrolyte. After 24 hours of anodic polarization, $Ti/IrO_2-Ta_2O_5$ coating mesh anode has much lower oxygen evolution overpotential and better corrosion performance than Pb-0.7% Ag lead anode [2].

It was reported that good DSA anode materials should have low overpotential, insoluble protective layer in electrolyte and have enough resistance to the mechanical and chemical action of oxygen evolution on the anodic surfaces [3]. RuO_2 , which is a platinum group metal ruthenium oxide, has a low overpotential. However, RuO_4 will be formed under the reaction of O_2 and dissolved continuously, resulting in the loss of active sub-

stances, which makes the poor service life of ruthenium coating in strong electrowinning environment. For improving the stability of active oxides, it is a feasible approach to add other inert components, such as Ta_2O_5 and SnO_2 , into RuO_2 coating, which can effectively protect the active. It was found that the IrO_2 and RuO_2 mixed compounds have good electrocatalytic properties due to their advanced properties of these two oxides by addition of IrO_2 to $RuO_2 + TiO_2$ coating [4].

$IrO_2-Ta_2O_5$ coating Ti based anodes containing different SnO_2 were prepared by thermal decomposition method. The electrocatalytic performance of the coatings were tested by cyclic voltammetry, polarization curve study and electrochemical impedance spectroscopy. The corrosion resistance of the coating was measured by enhanced life. The results show that after doping SnO_2 , the specific surface area of $IrO_2-Ta_2O_5$ coating on Ti based anode increases, also the oxygen evolution potential and total resistance of the coating rise, but the corrosion resistance decreases. When the content of SnO_2 is 7.7%, the comprehensive electrocatalytic performance is the best [3].

Zhang et al. (2017) had researched the mesh Ti/IrO_2 (30%)- Ta_2O_5 (70%) and the mesh Ti/MnO_2 DSA in a zinc electrolyte at

¹ HUNAN UNIVERSITY OF TECHNOLOGY, SCHOOL OF METALLURGICAL, ZHUZHOU, CHINA, 412002

² LAVAL UNIVERSITY, DEPARTMENT OF MINING, METALLURGICAL AND MATERIALS ENGINEERING, QUEBEC, QC, CANADA, G1K 7P4

³ HYDRO-QUÉBEC RESEARCH INSTITUTE, SHAWINIGAN, QC, CANADA, G9N 7N5

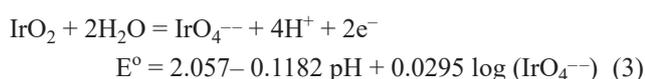
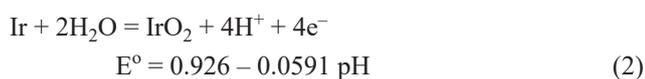
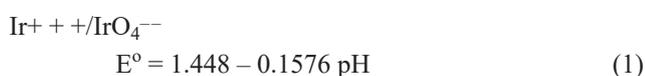
* Corresponding author: wei.zhang.1@ulaval.ca



a current density of 50 mA/cm² and 38°C, it was found that the Ti/IrO₂-Ta₂O₅ mesh DSA anode had the lower corrosion rate during the potential decay, the better performance and a higher current efficiency during polarization than the Ti/MnO₂ DSA anode [5].

IrO₂ has the widest electrocatalytic activity for oxygen evolution reaction in sulfuric acid electrolyte among the three coatings of IrO₂, RuO₂ and Ta₂O₅. Also, IrO₂ service life is 20 times of that of RuO₂. However, since IrO₂ is more expensive than RuO₂, other components, such as Ta₂O₅, are added to the coating for saving cost and improving coating performance [6]. In addition, IrO₂ is a good catalyst for the oxygen evolution reaction of DSA anode in the electrolytic solution containing chloride ions, so Ti/IrO₂ is also employed to extract zinc from zinc content waste liquid containing considerable amount of chloride ions [7].

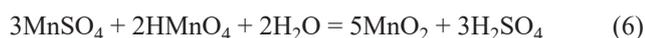
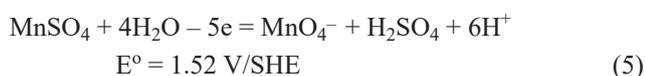
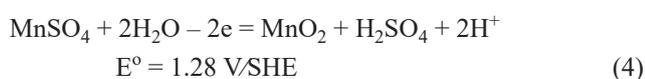
The surface electrochemical behaviour of DSA anodes is controlled by the Ir(III)/Ir(IV) redox transition as the surface properties [8]:



Manganese added into the zinc electrolyte leads to reduce the corrosion of anodes and minimizing the contamination of lead impurity in the zinc cathodes [9]. Manganese ions react in the process of surface oxidation on the DSA anode, forming soluble substance or insoluble manganese dioxide, which could passivate the DSA anode. Increase of concentrations of manganese ions during the zinc electrowinning can cause a significant decrease in current efficiency, which have to be removed or controlled when building up to a certain level. So the presence of manganese has dual effects, positive and negative, depending on its concentration in the electrolytes [10,11].

The particles of MnO₂, which are produced on the anodes, passivate the anode surface and lead to an increase in anode potential. Manganese oxide deposition blocks the catalytic sites on the DSA anodes [12]. Mn²⁺ ions in the electrolyte could be oxidized to MnO₄⁻ which was proposed to react immediately with Mn²⁺ to form Mn³⁺ and finally MnO₂. Manganese ions can be present as Mn(II), Mn(III), Mn(VII) and possibly also Mn(IV) in strongly acidic solutions [13]. It is apparent that a number of manganese species can be oxidized to form deposits on the surface of an electrode, with MnO₂ as the predominant product.

The reactions of Mn²⁺ on the anode are as follows [14]:



The oxidation of Mn²⁺ to Mn³⁺ and Mn²⁺ to MnO₄⁻ both have similar standard potentials of about 1.51 V.



The effect of certain compounds on the inhibition of MnO₂ formation has been studied using additives such as soluble phosphorous (V) and arsenic (III) [15]. For the neutralized zinc solution at pH 5, oxidative precipitation using a strong oxidant such as Caro's acid and SO₂/O₂ can selectively precipitate manganese as insoluble MnO₂ or Mn(OOH), leaving other impurities, e.g., Mg²⁺, Cl⁻, F⁻, etc. in the circuit. Solvent extraction of zinc using D2EHPA (di-2-ethylhexyl phosphoric acid) can selectively recover zinc from the solution and leave other impurities including manganese in the electrolytes [16].

Velayutham et al (1993) found that phosphoric acid (H₃PO₄) can be used to complex the Mn³⁺ ion and hence reduce its disproportionation of MnO₂. Also, it can stabilize the Mn³⁺ ion in the electrolyte, and the anodic peak current decreased as compared to that in the electrolyte with H₂SO₄ only [17]. Few additions of H₃PO₄ to the sulfuric acid may diminish the deposition of MnO₂ on the anodic surface during oxygen evolution reaction [18]. In addition, the inhibition of MnO₂ formation by arsenic and phosphorous compounds can be explained on the basis of preferential adsorption of such compounds on the electrode surface [16].

Ramachandran et al. (1985) studied the addition of phosphoric acid compounds as a deterrent for MnO₂ deposition using galvanostatic technique because of the probable role of these compounds in the inhibition of anodic formation of MnO₂ [19]. The presence of manganese in solution is deterrent for the operation of catalytic anodes since a coating of MnO₂ is formed on the anode surface, which results in reducing catalytic activity.

In this manuscript, to overcome the shortcoming of the DSA anodes, the electrochemical performance of the Ti/IrO₂-Ta₂O₅ mesh and plate anodes was studied in the zinc electrolyte containing different Mn²⁺ by recent electrochemical measurements such as electrochemical impedance tests and electrochemical noise measurements. 17 g/L and 35 g/L phosphoric acid was added to the zinc electrolyte to complex the manganic Mn³⁺ ion and hence reduce its disproportionation to MnO₂. This can result in increase of their service life, electrochemical performance and then replace of the traditional lead silver anodes. Also, the DSA can improve the quality of zinc deposit for the zinc electrowinning industry.

2. Experimental

2.1. Materials and sample preparation

The Ti/IrO₂-Ta₂O₅ mesh and plate anodes are mainly fabricated from Ti/ (30%)IrO₂-(70%)Ta₂O₅, which are provided by Hydro-Québec research institute. One plate of platinum and one

plate of Ti/IrO₂-Ta₂O₅ mesh and plate were used as cathode, and anode respectively. All plates were casted in polyester resin in order to obtain an exposed surface area of 1 cm². Ag, AgCl/KCl_(sat) (0.199 V/SHE) was used as reference electrode. The electrodes are mounted in three-cell electrode with inter distance of 2 cm. Before electrolysis, the cathode was manually polished by several grits SiC papers then washed by distilled water & ethanol and dried before the immersion in the electrolyte. While the anode was only washed by distilled water & ethanol and dried before the immersion in the electrolyte [5].

The zinc sulphate electrolytes used in this study were prepared from ZnSO₄·7H₂O, and pure H₂SO₄ (Conc. 98%) and 6, 9, and 12 g/L Mn²⁺, respectively. The cations of Mn²⁺ was added as the form of MnSO₄·2H₂O. The blank electrolytic solution was always prepared from 60 g L⁻¹ of Zn²⁺ and 170 g L⁻¹ of H₂SO₄. The standard zinc electrolyte was based on electrolytic solution with 6, 9, and 12 g L⁻¹ Mn²⁺. Reagents were supplied from Lab mat and VWR Canada. Small-scale galvanostatic electrolysis was performed in 1000 ml solution in double-glazed beaker. The solution was heated by the flow of thermostated water in order to maintain a constant working temperature. The electrolyte was stirred at 412 rpm by a magnetical stirrer (4 cm long and 1 cm in diameter) during the electrochemical measurements except for the CV and the ENM studies.

2.2. Experimental setup

Electrochemical studies were based on the analysis of cyclic voltammetric measurements and potentiodynamic polarization tests without agitation in atmospheric conditions by using potentiostat Gamry reference 3000. Cyclic voltammetry experiments were employed to measure the electrochemical performance of the Ti/IrO₂-Ta₂O₅ mesh and plate alloy electrodes. The potential was scanned from from -300 to 1800 mV vs OCP for the cathodic potentiodynamic polarization with a constant scan rate of 5 mV s⁻¹ [20].

After 24 h of polarization, the anode was held for 2 h of decay at open circuit potential (OCP). This is followed by linear polarization (LP) and electrochemical impedance spectroscopy (EIS) tests. LP measurements were carried out at ±20 mV with respect to corrosion potential (E_{corr}) at constant scan rate of 0.166 mV/s [21]. EIS tests were carried out at frequency range from 100 kHz to 0.01 Hz with an amplitude of 5 mV. The EIS data were examined using Gamry EchemAnalyst based on the appropriate equivalent electrical circuit [22]. After 24 h of electrolysis, two identical anodes were connected to zero resistance ammeter (ZRA) mode for 2 h controlled by Gamry model PC4/750 – USA. Also, after galvanostatic polarization, the anode was scanned employing scanning reference electrode technique (SRET) using EG&G Instruments model SVP100 – UK. The surface of specimen was adjusted and leveled in parallel with the surface of the Persoex tripod. The probe was lowered using the Z-axis control to negative direction to a distance of z50e100 mm from the specimen surface. The specimen was connected to the

negative input of the apparatus while the probe was connected to the positive one for free corrosion measurement mode. The signal was adjusted at 20 mV of sensitivity and vibrating amplitude of 20 mm. Each scan lasted 15 min for a total period of 2 h. All corrosion tests were performed at least in duplicates to assure a good reproducibility.

2.3. Consecutive series of electrochemical testing

The experimental were carried out by the following procedures: (a) Cyclic voltammetry, (b) Chronopotentiometry (galvanostatic), (c) Open circuit potential, (d) Electrochemical noise, (e) Electrochemical impedance measurements, (f) Scanning reference electrode technique.

3. Results and discussion

3.1. Cyclic voltammetry study for DSA anode

Fig. 1 shows cyclic voltammograms of the fresh surfaces of the DSA-mesh electrodes in 0.5 M/L H₂SO₄ with and without 9 g/L Mn²⁺ addition at a scan rate of 5 mV/s at 39°C without agitation. It was found that addition of 9 g/L Mn²⁺ into the sulfuric acid solution decreased the values of oxidation peaks in the sulfuric acid solution. The reason is that addition of Mn²⁺ into sulfuric acid solution promoted a formation of MnO₂ layer on the surface of DSA anode and decreased the value of current density.

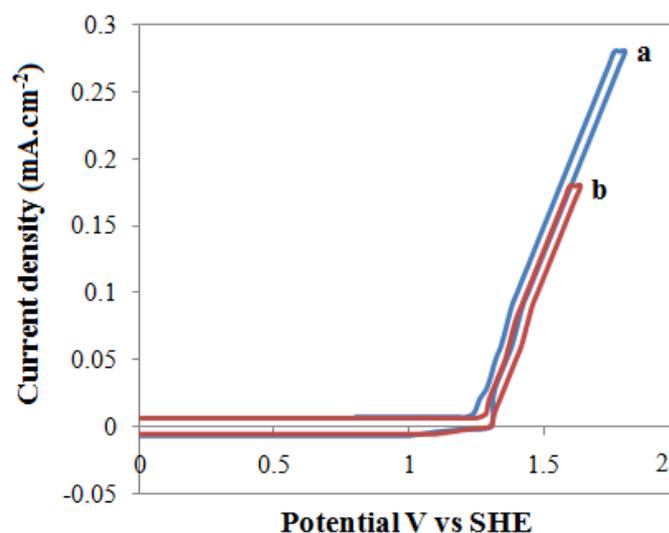


Fig. 1. Cyclic Voltammograms before electrolysis for DSA-mesh electrodes in 0.5 M/L H₂SO₄ containing different contents of Mn²⁺ with addition of (a) 0, (b) 9 g/L at a scan rate of 5 mV/s and 39°C without agitation

The effect of phosphoric acid on the inhibition of MnO₂ formation has been studied using cyclic voltammetric technique. Fig. 2 shows cyclic voltammograms of the fresh surfaces of the DSA-mesh electrodes in 0.5 M/L H₂SO₄ containing 9 g/L Mn²⁺

in absence and in presence of 17 and 35 ml/L phosphoric acid addition at a scan rate of 5 mV/s at 39°C without agitation. It can be observed the three oxidation peaks at around 1.5 V were corresponding to: $2\text{H}_2\text{O} - 4\text{e} \rightarrow \text{O}_2 + 4\text{H}^+$ (9) [23]. The oxidation peak in the solution with 35 ml/L phosphoric acid addition is highest, followed by that with 17 ml/L phosphoric acid addition and that without addition of phosphoric acid. It means that addition of 17 and 35 ml/L phosphoric acid to the solution can complex the manganic ion and increase oxidation peak height. Also, the cathodic peak at 1.2 to 1.3 V due to reduction of MnO_2 is observed only in the electrolyte without phosphoric acid. The reduction reaction is corresponding to: $\text{MnO}_2 + \text{H}_2\text{SO}_4 + 2\text{H}^+ + 2\text{e} = \text{MnSO}_4 + 2\text{H}_2\text{O}$ (10) since the potential of reduction reaction of MnO_2 is 1.28 V/SHE. In addition, some MnO_2 particles were also observed to suspend in the electrolyte.

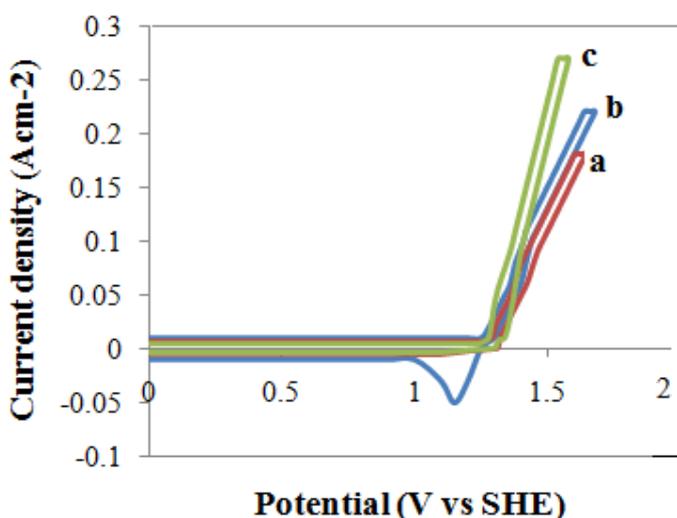


Fig. 2. Cyclic Voltammograms before electrolysis for DSA-mesh electrodes in 0.5 M H_2SO_4 containing 9 g/L Mn^{2+} with addition phosphoric acid of (a) 0; (b) 17 g/L; (c) 35 g/L at a scan rate of 5 mV/s and 39°C without agitation

3.2. Anodic potential for the oxygen evolution reaction (ORE) on the DSA anode in acid zinc sulphate electrolyte with different contents of Mn^{2+}

The anodic potentials of anodic galvanostatic polarization at 48 mA/cm² and 39°C for the DSA-mesh anode in acid zinc sulphate electrolyte containing 6, 9 and 12 g/L Mn^{2+} with time have been investigated in Fig. 3. After five hours of electrolysis, the solution became purple red because of the formation of permanganate ions.

At the end of the electrolysis, the potentials of the DSA-mesh anode in standard electrolyte with addition of 6 g/L Mn^{2+} , 9 g/L Mn^{2+} and 12 g/L Mn^{2+} were 1638, 1653, and 1686 mV/SHE, respectively. The anodic potentials increased from 1653 to 1686 mV when manganese ion was added from 9 to 12 g/L. The reason is that more manganese ion added in the zinc electrolyte resulted in more manganese oxides layer on the surfaces of the DSA-mesh anodes. This leads to higher overpotential on

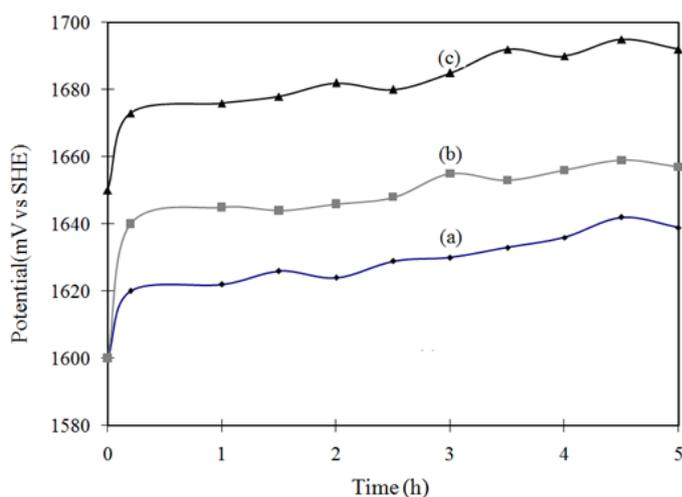


Fig. 3. 5 h galvanostatic test of DSA-mesh anode at 48 mA/cm² and 39°C in the zinc electrolyte containing (a) 6 g/L Mn^{2+} ; (b) 9 g/L Mn^{2+} ; (c) 12 g/L Mn^{2+}

the DSA-mesh anodes with more anodic potential. It was found that the anodic potential was increased from 1638 to 1653 mV when addition of manganese ion increased from 6 to 9 g/L, the range of potential increased for addition manganese ion from 6 to 9 g/L is much less than that of addition manganese ion from 9 to 12 g/L, it is possible that the manganese ion added to the zinc electrolyte has a function of depolarization [13].

To complex the manganic Mn^{3+} ion and hence reduce its disproportionation of MnO_2 , the anodic potentials of the DSA-mesh anodes were measured at a current density of 48 mA/cm² and 39°C in acid zinc sulphate electrolyte containing 9 g/L Mn^{2+} , or 9 g/L Mn^{2+} with addition of 17 and 35 ml/L H_3PO_4 on DSA-mesh anodes for five hours. The anodic potentials vs time curves are shown in Fig. 4.

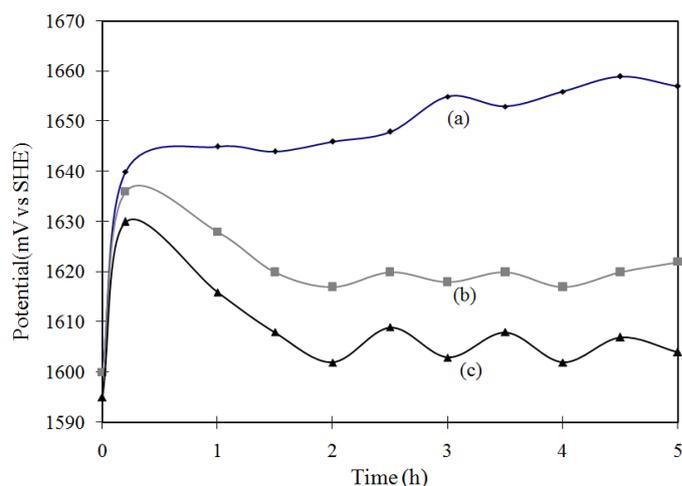
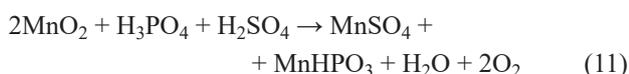


Fig. 4. 5 h galvanostatic test of DSA-mesh anode at 48 mA/cm² and 39°C in the zinc electrolyte containing (a) 9 g/L Mn^{2+} ; (b) 9 g/L Mn^{2+} and 17 ml/L H_3PO_4 ; (c) 9 g/L Mn^{2+} and 35 ml/L H_3PO_4

Fig. 4 shows that there is a cell voltage relating to the standard electrolyte with addition of different concentrations of

phosphoric acid. When the different concentrations of phosphoric acid were added to the electrolyte, it results in the decrease of the anodic potentials. At the end of 5 h galvanostatic test, the anodic potentials for the DSA anode with 9 g/L Mn^{2+} alone (a), 9 g/L Mn^{2+} with addition of 17 ml/L H_3PO_4 (b) and 9 g/L Mn^{2+} with 35 ml/L H_3PO_4 (c) were 1653, 1624 and 1607 mV/SHE, respectively. It has been shown that the lower potential can be maintained for longer periods when there is sufficient phosphoric acid to complex the manganic ion [16]. The presence of phosphoric acid confirms the reduction of MnO_2 on the surface of the DSA anode. Few additions of H_3PO_4 to the sulphuric acid can diminish the deposition of MnO_2 on the surface of anode during oxygen evolution reaction. The reaction should be as follows [16].



3.3. Potential decay of DSA mesh anode after 5 h galvanostatic polarization in acid zinc sulphate electrolyte with 6, 9 and 12 g/L Mn^{2+}

After 5 h galvanostatic polarization, the corrosion potential decay of one hour was recorded, then potentiodynamic measurements were performed to measure the corrosion potential (E_{corr}) and corrosion current (i_{corr}). The tests were followed by second hour potential decay and another potentiodynamic measurement. The curves of potential decay of the DSA-mesh anode following 5 h polarization in acid zinc sulphate electrolyte containing 6, 9 and 12 g/L Mn^{2+} respectively are shown in Fig. 5. The corrosion potential (E_{corr}) and corrosion current (i_{corr}) of the DSA anode after the first hour and the second hour potential decay following 5 h galvanostatic polarization at 48 mA/cm² in the zinc electrolyte containing 6, 9 and 12 g/L Mn^{2+} , respectively, are shown in TABLE 1.

Fig. 5 shows that the potential of the DSA-mesh anode in the zinc electrolyte containing 12 g/L Mn^{2+} drop slowly, and

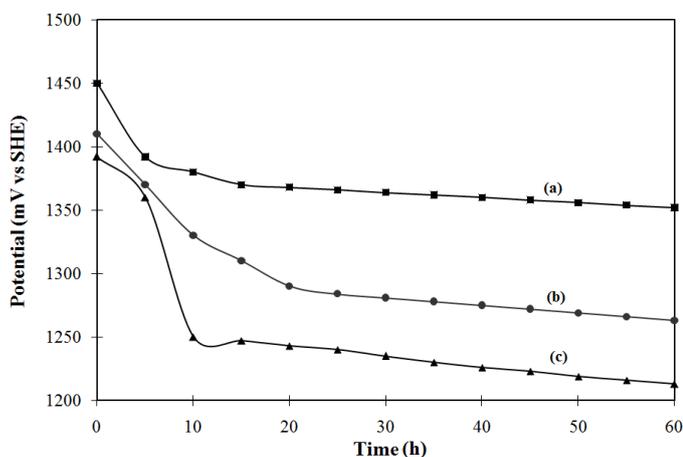


Fig. 5. Potential decay of the first hour for the DSA-mesh anode after 5 hours of galvanostatic polarization at 48 mA/cm² and 39°C in the zinc electrolyte containing (a) 12 g/L Mn^{2+} ; (b) 9 g/L Mn^{2+} ; (c) 6 g/L Mn^{2+}

had a longest potential plateaus among the DSA anode in the zinc electrolyte containing different contents of manganese ion around 1370 mV/SHE corresponding to the theoretical potential value of the $\text{MnO}_2/\text{Mn}^{2+}$ equilibrium. This shows a spontaneous transformation of manganese dioxide into manganese sulphate because thermodynamically manganese dioxide is unstable on the surface of manganese in the sulphuric acid solution [24]. The potentials at the end of 1 hour for the DSA-mesh anode in acid zinc sulphate electrolyte containing 6 g/L Mn^{2+} , 9 g/L Mn^{2+} , 12 g/L Mn^{2+} were 1212, 1233, and 1352 mV vs. SHE respectively. After the galvanostatic polarization, it was observed that the less potential leads to the less corrosion rate for the DSA-mesh anode in a bath with MnSO_4 addition.

TABLE 1

Corrosion potentials, corrosion currents of the DSA-mesh anodes after one hour and two hour potential decay in the zinc electrolyte containing 6 g/L Mn^{2+} , 9 g/L Mn^{2+} and 12 g/L Mn^{2+} with agitation

Anodes Mn^{2+} contents	E_{corr} (mV vs SHE)		i_{corr} (μAcm^{-2})	
	One hour decay	Two hour decay	One hour decay	Two hour decay
6	1212	714	65.3	46.7
9	1263	743	51.6	40.6
12	1352	894	51.4	38.8

TABLE 1 shows that after one and two hour potential decay following 5 hours of galvanostatic polarization at 48 mA/cm² in acid zinc sulphate electrolyte containing 6 g/L Mn^{2+} , 9 g/L Mn^{2+} and 12 g/L Mn^{2+} respectively with agitation at 39°C, it was seen that addition of more manganese into the zinc electrolyte results in the more decrease of the corrosion rate of the DSA-mesh anode. The corrosion of the DSA-mesh anode after the second decay was lower than that after the first decay.

Fig. 6 shows that the potential decay of the DSA anode in the zinc electrolyte containing 9 g/L Mn^{2+} , or 9 g/L Mn^{2+} with addition of 17 and 35 ml/L H_3PO_4 on DSA-mesh anode, respec-

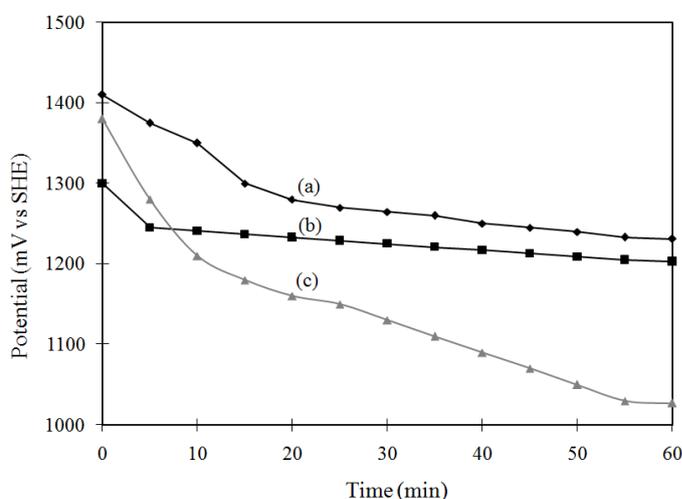


Fig. 6. Potential decay of the DSA-mesh anode after 5 hours of galvanostatic polarization at 48 mA/cm² and 39°C in the zinc electrolyte containing (a) 9 g/L Mn^{2+} ; (b) 9 g/L Mn^{2+} and 17 ml/L H_3PO_4 ; (c) 9 g/L Mn^{2+} and 35 ml/L H_3PO_4

tively. The potentials at the end of 1 hour for the DSA-mesh anode in acid zinc sulphate electrolyte containing 9 g/L Mn^{2+} , or 9 g/L Mn^{2+} with addition of 17 and 35 ml/L H_3PO_4 on DSA-mesh anodes were 1263, 1235, and 1048 mV vs. SHE respectively. The corrosion potential (E_{corr}) and corrosion current (i_{corr}) of the DSA-mesh anode after the first hour and the second hour potential decay following 5 h galvanostatic polarization at 48 mA/cm² in the zinc electrolyte containing 9 g/L Mn^{2+} , or 9 g/L Mn^{2+} with addition of 17 and 35 ml/L H_3PO_4 additions were shown in TABLE 2.

As shown in Fig. 6, the open circuit potential was lower when phosphoric acid was added to the electrolyte. The lower potential can be maintained for longer periods when there is sufficient phosphoric acid to complex the manganic ion. Also, it was found that addition of 35 ml/L H_3PO_4 to the zinc electrolyte decreased more potential value than that of 17 ml/L H_3PO_4 . It means that addition of 35 ml/L H_3PO_4 into the zinc electrolyte can reduce more MnO_2 to MnSO_4 than that of 17 ml/L H_3PO_4 .

TABLE 2

Corrosion potentials, corrosion currents of the DSA-mesh anode after one hour and two hour potential decay in the zinc electrolyte containing 9 g/L Mn^{2+} with addition of 0, 17 and 35 ml/L H_3PO_4 with agitation, respectively

H_3PO_4 contents	E_{corr} (mV vs SHE)		i_{corr} (μAcm^{-2})	
	One hour decay	Two hour decay	One hour decay	Two hour decay
0	1263	743	51.6	40.6
17	1235	718	59.2	48.4
35	1048	549	54.7	43.5

TABLE 2 shows that addition of 17 ml/L H_3PO_4 into the zinc electrolyte containing 9 g/L Mn^{2+} results in an increase (~12.7%) the corrosion rate of the DSA-mesh anode. It implies that addition 17 ml/L H_3PO_4 to the electrolyte reduced the MnO_2 layer and increased the corrosion rates of DSA-mesh anodes. However, the addition of 35 ml/L H_3PO_4 into the zinc electrolyte containing 9 g/L Mn^{2+} results in a decrease (~7.6%) of the corrosion rate of the DSA anode compared to that of 17 ml/L H_3PO_4 , it is very possible that the H_3PO_4 forms a phosphoric oxide layer on the surface of DSA anode and protects it from the corrosion. Also, the corrosion rates and potential values of the DSA anode after the second decay were lower than that after the first decay.

3.4. Electrochemical noise measurements after galvanostatic polarization

Zero resistance ammeters in electrochemical noise measurements were employed to monitor the corrosion of DSA-mesh anode during electrolysis in situ. For the measurements, the most important parameters of the statistical analysis in the time domain, is the noise resistance (R_n), defined as the proportion of a standard deviation of the potential noise to that of a current

noise which is related to the polarization resistance (R_p). The opposite R_n is admittance, unit of Siemens (S), which is ratio to the corrosion rate [25,26]. It was found that electrochemical noise is a good technique to investigate the influence of silver on the corrosion rate of lead anodes. After 5 h of polarization in the zinc sulphate acidic solutions with different Mn^{2+} contents, it was carried out for the evolution of admittance “ $1/R_n$ ” (mS) during 16 h of decaying of the DSA-mesh anodes (Fig. 7). In situ measurements in a continuous way were summarized every 1 h period in one point by statistics.

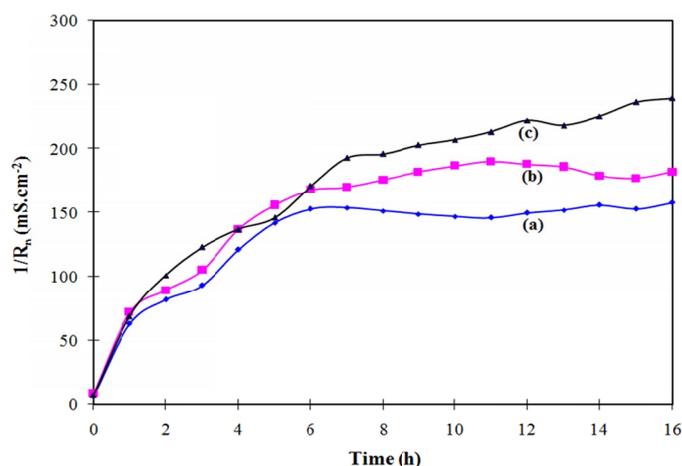


Fig. 7. Evolution of admittance “ $1/R_n$ ” (mS/cm²) of the DSA-mesh anodes following 5 h galvanostatic polarization during 16 h immersion period in the zinc electrolyte containing (a) 12 g/L Mn^{2+} ; (b) 9 g/L Mn^{2+} and (c) 6 g/L Mn^{2+}

Seen from Fig. 7, it was found that the DSA mesh anode in the zinc electrolyte containing 12 g/L Mn^{2+} (149 mS/cm²) had the lowest corrosion rate among the three test results, followed by 9 g/L Mn^{2+} (176) and 6 g/L Mn^{2+} (231) after the 16 h decaying following 5 h polarization at 48 mA/cm². It means that the DSA mesh anode in the zinc electrolyte containing higher manganese ion content had better corrosion behaviour during the current interrupt.

Evolution of admittance “ $1/R_n$ ” (mS/cm²) of the DSA mesh anodes following 5 h galvanostatic polarization at 48 mA/cm² and 39°C in the zinc electrolyte containing 9 g/L Mn^{2+} without and with 17 ml/L H_3PO_4 or 35 ml/L H_3PO_4 is shown in Fig. 8.

Seen from Fig. 8, it was found that the DSA mesh anode in the zinc electrolyte containing 9 g/L Mn^{2+} with addition of 17 ml/L H_3PO_4 (198 mS/cm²) had the highest corrosion rate among the test results, followed by that without addition (176) and with addition of 35 ml/L H_3PO_4 (141) and, respectively. It means that addition of 17 ml/L H_3PO_4 to the zinc electrolyte can decrease the MnO_2 layer and increase the corrosion rate of the DSA-mesh anode. However, the addition of 35 ml/L H_3PO_4 to the zinc electrolyte can decrease the corrosion rate of the DSA mesh anode, since addition of 35 ml/L H_3PO_4 to the solution resulted in the decrease the MnO_2 layer and the formation of phosphoric oxide layer in the zinc electrolyte during the current interrupt.

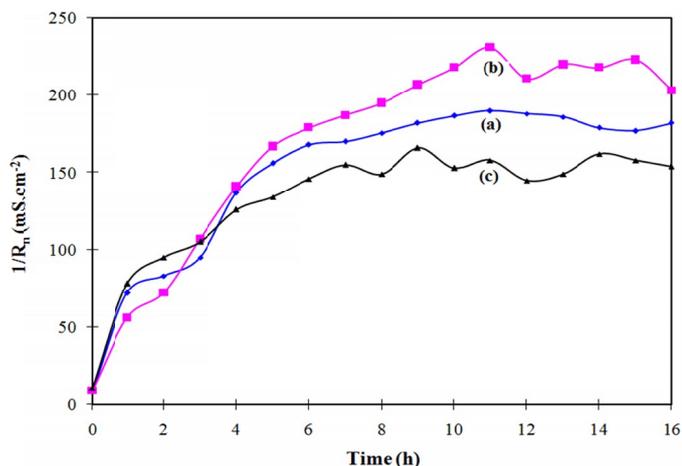


Fig. 8. Evolution of admittance “ $1/R_n$ ” (mS/cm²) of the DSA mesh anodes following 5 h galvanostatic polarization at 48 mA/cm² and 39°C in the zinc electrolyte containing (a) 9 g/L Mn²⁺; (b) 9 g/L Mn²⁺ and 17 ml/L H₃PO₄; (c) 9 g/L Mn²⁺ and 35 ml/L H₃PO₄

3.5. Electrochemical impedance measurements of polarization resistance after 5 hours galvanostatic polarization

In this test, the DSA working electrode was introduced into the cell and 5 h galvanostatic polarization at 48 mA/cm² was started immediately in the zinc electrolyte containing 6, 9, and 12 g/L Mn²⁺, respectively. Then the measurements of electrochemical impedance at open circuit potential were carried out and the polarization resistance corresponding to corrosion resistance was calculated.

Fig. 9 displays the Nyquist plots of electrochemical impedance measurement after 5 h galvanostatic polarization at 48 mA/cm² for the DSA mesh anode in the zinc electrolyte containing 6, 9, 12 g/L Mn²⁺.

The data of the DSA mesh anode after 5 h galvanostatic polarization at 48 mA/cm² in the zinc electrolyte with different

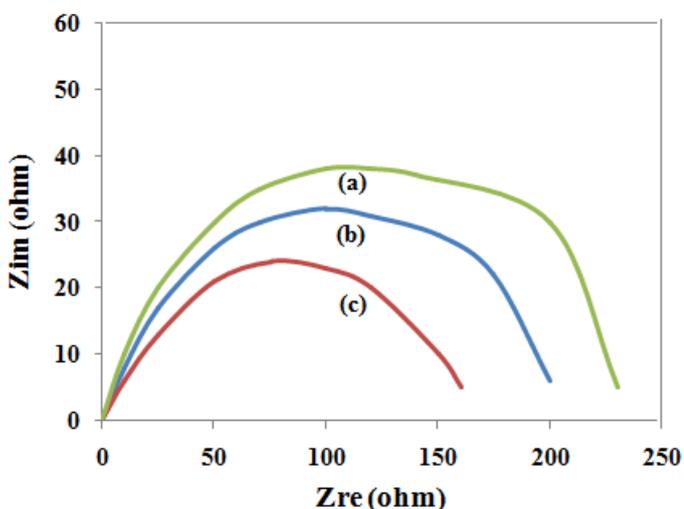


Fig. 9. Nyquist plots of the DSA mesh anode after 5 h galvanostatic polarization at 48 mA/cm² at 39°C in the zinc electrolyte containing (a) 12 g/L Mn²⁺; (b) 9 g/L Mn²⁺; (c) 6 g/L Mn²⁺

contents of Mn²⁺ at 39°C obtained by fit circle of “PowerSINE” software are 137, 186 and 223 ohm for addition of 6, 9, 12 g/L Mn²⁺, respectively. The DSA mesh anode in the zinc electrolyte containing 12 g/L Mn²⁺ had the highest corrosion resistance among the three corrosion resistances in the zinc electrolyte from that containing 9, 6 g/L Mn²⁺, respectively. It means that the impedance resistance of the DSA mesh anode increased with addition of Mn²⁺.

Fig. 10 displays the Nyquist plots of electrochemical impedance measurement after 5 h galvanostatic polarization at 48 mA/cm² for the DSA mesh anode in the zinc electrolyte containing 9 g/L Mn²⁺; 9 g/L Mn²⁺ with additions of 17 and 35 ml/L H₃PO₄, respectively.

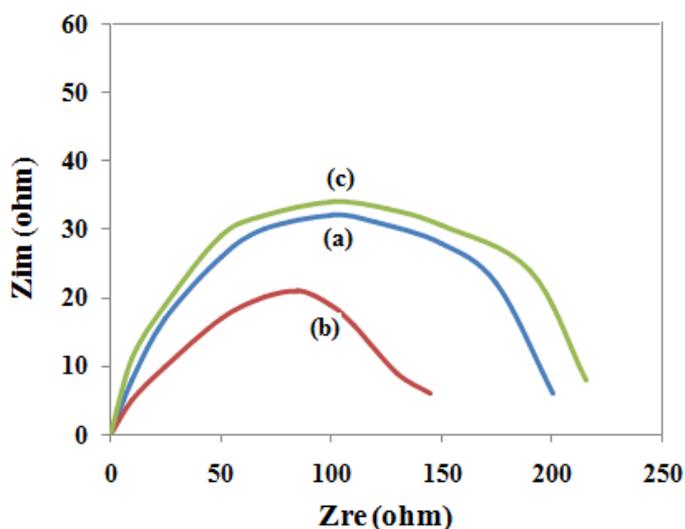


Fig. 10. Nyquist plots of DSA-mesh anode after 5 h galvanostatic polarization at 48 mA/cm² in the zinc electrolyte containing (a) 9 g/L Mn²⁺; (b) 9 g/L Mn²⁺ and 17 ml/L H₃PO₄; (c) 9 g/L Mn²⁺ and 35 ml/L H₃PO₄

The data of the DSA mesh anode after 5 h galvanostatic polarization at 48 mA/cm² in the zinc electrolyte with different contents of Mn²⁺ at 39°C obtained by fit circle of “PowerSINE” software are 186, 167 and 205 ohm for addition of 9 g/L Mn²⁺, or 9 g/L Mn²⁺ with 17 and 35 ml/L H₃PO₄, respectively. The DSA mesh anode in the zinc electrolyte containing 9 g/L Mn²⁺ with 35 ml/L H₃PO₄ addition had the highest impedance resistance among the three impedance resistances in the zinc electrolyte containing 9 g/L Mn²⁺ with different contents of H₃PO₄. It means that the addition of 35 ml/L H₃PO₄ to the zinc electrolyte can increase impedance resistance of the DSA mesh anode.

3.6. Scanning reference electrode technique for the corrosion of the DSA anodes

Scanning reference electrode technique (SRET) is a useful technique in determining the form of corrosion especially for the localized one. Two additives of Mn²⁺ and H₃PO₄ were chosen to be compared to blank electrolyte in order to examine the effect of the anionic part on the corrosion form of the DSA plate anode.

After galvanostatic polarization, the anode was scanned employing SRET in acidic zinc sulfate electrolyte for 2 h. The specimen surface was scanned for surface area of 8 mm (X-axis) and 6 mm (Y-axis). Each scan lasted approximately 15 min and a rest of 1 min after each one in order to enable the probe to relocate to the first scanning point. After each scan (every 15 min), the measured potential was plotted against time and 2D maps for the cathodic and anodic zones on the surface are given (Fig. 11). Seen from the Fig. 11, it can be observed that the potential differences were distributed into different zones corresponding to neutral, lower intense cathodic and higher anodic activities. The deep blue area corresponds to the higher anodic zone (corrosion zone), green area represents neutral zone and the red area means the higher cathodic zone [27]. Fig. 11 displays 2-D corrosion activity map of the DSA plate electrodes in the zinc sulfuric acid solution containing Mn^{2+} and H_3PO_4 additives after 2 hours immersion at 25°C. Moreover, the observed form of corrosion from 2D maps was quasi uniform on the center surface of the DSA plate anode. It is very possibly due to the formed protective oxide

film on the center of the anodic surface. However, the corrosion products on the corners and edges of the DSA plate anodes were observed during the scanning period, the blue color represents the potentials of localized corrosion. It means that localized corrosion appears on the corners and edges of the DSA anodes.

The term “quasi electromotive force” (QEMF) is used to express the potential difference between the most active cathode and the most active anode on the surfaces of the DSA plate electrodes in the zinc sulfuric acid solution. It is reported that higher QEMF corresponds to higher corrosion rate of the active electrodes [28]. Fig. 12 shows the QEMF of corrosion cell on the surface as a function of immersion time.

Fig. 12 shows that during 2 h polarization, the DSA plate anode in the zinc electrolyte containing 9 g/L Mn^{2+} and 17 ml/L H_3PO_4 had the highest QEMF, followed by that containing 9 g/L Mn^{2+} ; and that containing 9 g/L Mn^{2+} and 35 ml/L H_3PO_4 . It means that the DSA plate anode in the zinc electrolyte containing 9 g/L Mn^{2+} and 35 ml/L H_3PO_4 had the best corrosion resistance.

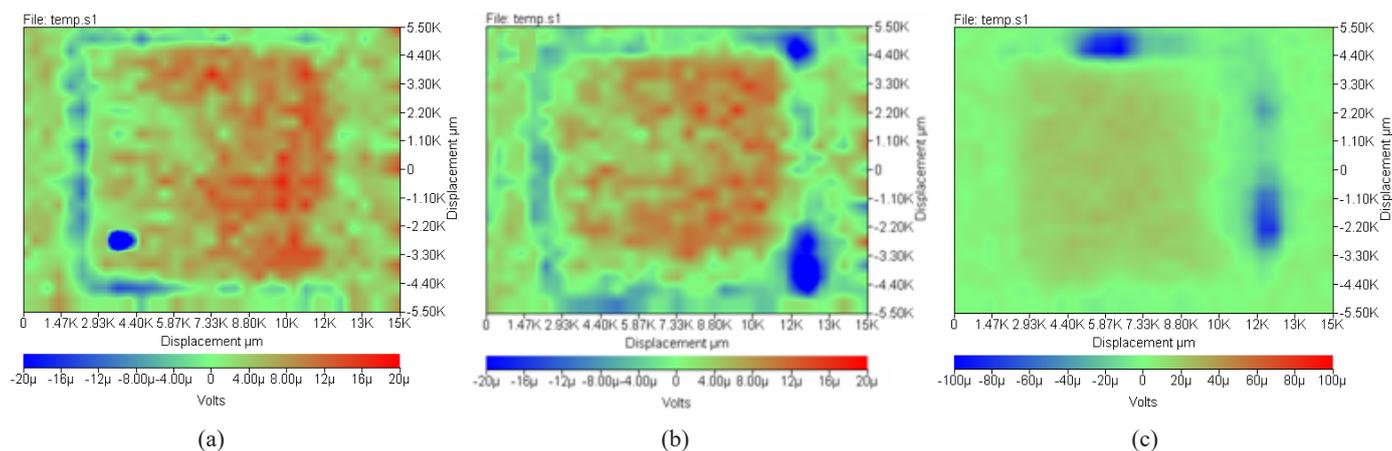


Fig. 11. Potential distribution on the DSA plate anode in the zinc electrolyte containing (a) 9 g/L Mn^{2+} ; (b) 9 g/L Mn^{2+} and 17 ml/L H_3PO_4 ; (c) 9 g/L Mn^{2+} and 35 ml/L H_3PO_4 at the end of one hour of polarization at 48 mA/cm² in the zinc sulfuric acid solution

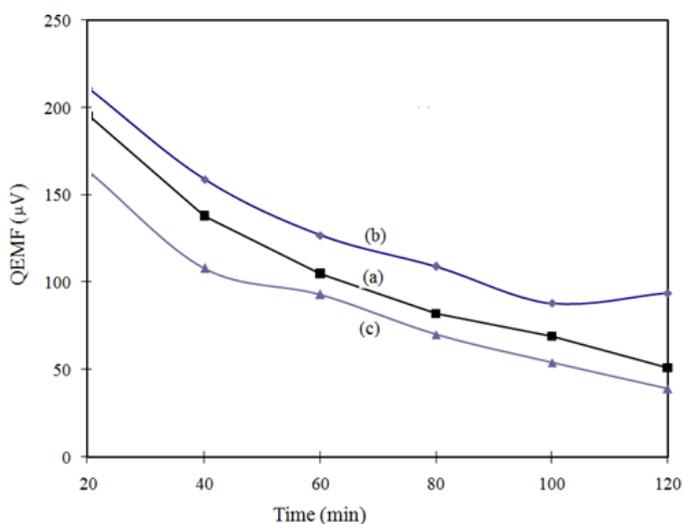


Fig. 12. QEMF evolution of the DSA plate anode in the zinc electrolyte containing (a) 9 g/L Mn^{2+} ; (b) 9 g/L Mn^{2+} and 17 ml/L H_3PO_4 ; (c) 9 g/L Mn^{2+} and 35 ml/L H_3PO_4

4. Conclusions

To overcome the shortcoming of the DSA anodes, the electrochemical performance of the Ti/IrO₂-Ta₂O₅ mesh and plate anodes was studied in the zinc electrolyte containing different Mn^{2+} by recent electrochemical measurements such as electrochemical impedance tests and electrochemical noise measurements. 17 g/L and 35 g/L phosphoric acid was added to the zinc electrolyte to complex the manganic ion. It has then been found that the anode potentials were lower when phosphoric acid was added to the electrolyte and the lower potential can be maintained for longer periods when there is sufficient phosphoric acid to complex the manganic ion. The presence of phosphoric acid confirmed the reduced formation of MnO_2 on the anode DSA-mesh for both concentrations.

After consecutive series of electrochemical testing, the following conclusions can be obtained:

- (a) cyclic voltammetry study before polarization shows that the oxidation peak in the solution with 35 ml/L phosphoric acid addition is highest, followed by that with 17 ml/L phosphoric acid addition and that without addition of phosphoric acid.
- (b) Addition of H_3PO_4 to the zinc electrolyte led to the decrease of potential value of DSA anode. The anodic potential of DSA anode in zinc electrolyte with 35 ml/L H_3PO_4 was lower (17 mV) than that in zinc electrolyte with 17 ml/L H_3PO_4 . Also, the potentials of the DSA-mesh anode in the zinc electrolyte with the addition of 6, 9, and 12 g/L Mn^{2+} were 1638, 1653, and 1686 mV/SHE, respectively.
- (c) After 16 h decay following 5 h polarization at 48 mA/cm^2 , the DSA mesh anode in the zinc electrolyte containing 12 g/L Mn^{2+} (149 mScm^{-2}) had the lowest corrosion rate among the test results, followed by 9 g/L Mn^{2+} (176 mScm^{-2}) and 6 g/L Mn^{2+} (231 mScm^{-2}).
- (d) Addition of 35 ml/L H_3PO_4 to the zinc electrolyte can decrease the corrosion rate ($4.5 \mu\text{A/cm}^2$) of the DSA mesh anode compared to that of 17 ml/L H_3PO_4 in the zinc electrolyte during the current interrupt
- (e) The impedance resistance of the DSA mesh anode increased from 137 to 223 ohm with increase of Mn^{2+} addition from 6 to 12 g/L.
- (f) Addition of 35 ml/L H_3PO_4 to the zinc electrolyte can form a phosphate oxide layer on the surface of DSA anode and increase impedance resistance.
- (g) The positive effect of phosphoric acid can be used to complex the manganic Mn^{3+} ion and hence reduce its disproportionation to MnO_2 . Various concentrations of phosphoric acid (17 and 35 g/L) were added to the zinc electrolyte containing 9 g/L Mn^{2+} , more addition of phosphoric acid to the solution results in more complex the manganic Mn^{3+} ion.
- (h) Scanning reference electrode technique shows that the DSA plate anode in the zinc electrolyte containing 9 g/L Mn^{2+} and 17 ml/L H_3PO_4 had the highest QEMF, followed by that containing 9 g/L Mn^{2+} ; and that containing 9 g/L Mn^{2+} and 35 ml/L H_3PO_4 .

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