

# **Conductivity Method as a New Monitoring Technique for Corrosion and Corrosion Inhibition Processes of Zinc Metal**

Abdelmnim M. Altwaiq<sup>1</sup>, Sa'ib J. Khouri<sup>2\*</sup>, Rami A. Abdel-Rahem<sup>1</sup>, Ahmad K. Alkhawaldeh<sup>3</sup>

<sup>1</sup>Department of Chemistry, College of Arts and Sciences, University of Petra, Amman, Jordan <sup>2</sup>Department of Basic Sciences, American University of Madaba, Amman, Jordan <sup>3</sup>Department of Chemistry, The University of Jordan, Amman, Jordan Email: \*s.khouri@aum.edu.jo

How to cite this paper: Altwaiq, A.M., Khouri, S.J., Abdel-Rahem, R.A. and Alkhawaldeh, A.K. (2020) Conductivity Method as a New Monitoring Technique for Corrosion and Corrosion Inhibition Processes of Zinc Metal. *American Journal of Analytical Chemistry*, **11**, 349-361. https://doi.org/10.4236/ajac.2020.1110028

**Received:** October 4, 2020 **Accepted:** October 26, 2020 **Published:** October 29, 2020

Copyright © 2020 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

http://creativecommons.org/licenses/by/4.0/

# Abstract

The electrical conductivity method was successfully applied as a new monitoring technique to monitor the corrosion and corrosion inhibition processes of zinc metal. Measurements of electrical conductivity at 20.0°C of three different corrosive solutions (HCl, NaOH, and NaCl) were performed with two different concentrations (0.10 and 1.00 M) containing zinc sheets in the absence and presence of four different concentrations of sodium lignosulfonate (1.0, 5.0, 10.0, and 20.0 mM). The analysis of curves that illustrates the changes in electrical conductivity of these solutions provides qualitative information about the strength of corrosion as well as the extent of corrosion inhibition behavior. The results obtained from electrical conductivity measurements revealed that sodium lignosulfonate was an effective corrosion inhibitor in acidic medium (for both 0.10 and 1.00 M HCl) in which it converted into lignosulfonic acid, but was less effective in salt and alkaline media.

# **Keywords**

Conductivity, Monitoring Technique, Corrosion, Corrosion Inhibitor, Lignosulfonate

# **1. Introduction**

Corrosion monitoring has been routinely practiced by many researchers in the last decades to determine the amount of corrosion and the rate of metal loss in the environment [1]. Corrosion measurement techniques play a significant role in determining the critical factors of corrosion and in reducing their effects [2].

Some of the analytical techniques include the drawing off fluid samples for analysis in laboratories where the areas of interest under this item are the concentration of metal ions, oxygen counts, electrical conductivity, and pH measurements [3].

The electrochemical corrosion monitoring techniques such as polarization techniques, potentiometric methods, and galvanic sensors are complicated and require particular expertise in using nitrogen gas for isolation the solutions from oxygen [1]. Unlike the previous electrochemical techniques, the electrical conductivity method is available, simple, and not affected by oxygen pressure and its results are easy to interpret [4]. In addition, among the techniques recently developed, electrochemical noise tests have proven to be beneficial as a method of determining the corrosion rate of certain passive materials, although scientists are striving to interpret conflicting results [5] [6]. In relation to evaluating corrosion for electrochemical phenomena and providing higher reliability, modern study has created agreement on the technique of electrical conductivity that is rapid and does not seriously harm the structure during implementation. The dynamics of the connected or mobile charges on the quantity of interface areas or fluid or solid material can be investigated [7] [8]. Therefore, this study focuses on the electrical conductivity measurements to monitor the corrosion inhibition behavior of lignosulfonate (LS) as sodium salt, which was studied for the first time. Other corrosion monitoring techniques such as weight loss and potentiodynamic polarization were studied before by our research group [9].

Based on their resistance to corrosion, metals and non-metals are contrasted. The attack rate of each material must be quantitatively specified in order to make such comparisons meaningful. In a number of distinct units corrosion rates can be provided using various conductivity measurements of the solution. A useful way to determine the corrosion rate is by immersing a sample for a certain amount of moment in a corrosive setting and measuring the solution's conductivity over that moment [4] [10].

Sodium lignosulfonate contains both hydrophilic and hydrophobic groups (**Figure 1**). It is an anionic surfactant, processing a certain degree of surface activity, which may promote surface adsorption and hence have application in corrosion inhibition process [11].

The corrosion rate of many metals has been improved, except for zinc, which has the most stable surface. Furthermore, zinc is known for its sacrificial properties for corrosion inhibition. Zinc atoms form a protective film of zinc oxide that prevents the zinc atoms below it from being further oxidized [12].

This study aims at measuring the variations of electrical conductivity of three different corrosive media containing zinc sheets in the absence and presence of four different concentrations of lignosulfonate to study both corrosion and corrosion inhibition processes. The three selected corrosive media were HCl solutions (1.00 M and 0.10 M), NaOH solutions (1.00 M and 0.10 M) and NaCl solutions (5.0% and 0.50% w/w).



Figure 1. The chemical structure of sodium lignosulfonate.

# 2. Materials and Methods

#### 2.1. Materials Used

Pure zinc sheets (99.0%) were purchased from Sigma-Aldrich (UK). Sodium lignosulfonate (powder form) was provided from Gainland Chemical Co (Deeside, UK). 0.10 M HCl and 1.00 M HCl solutions were prepared from a concentrated HCl solution purchased from Merck (UK). Solutions of 0.10 M and 1.00 M NaOH and solutions of 0.50% and 5.0% (w/w) NaCl were prepared from extra pure NaOH and NaCl that were provided from S.C. Chemical Co (New Berlin, USA). All solutions were prepared using deionized water.

#### 2.2. Electrical Conductivity Measurements

Zinc sheets (2.0 cm  $\times$  2.0 cm  $\times$  0.025 cm) were polished down by emery papers of 100 - 800 grit and degreased with ethanol, then they were immersed inside a 100 mL beaker covered with paraffin film contains different corrosive solutions (HCl, NaOH, and NaCl) in the presence and absence of 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate at 20°C. All experiments were made under stirring conditions of 450 revolutions per minute (rpm), and the values of electrical conductivity were followed with time. The experiment was done many times and the average of high precision electrical conductivity readings was used.

The electrical conductivity of the investigated solutions was measured using CC-501 conductometer (Elmetron, Witosa, Poland). The meter is fitted with custom LCDs to allow the measured function and temperature to be observed simultaneously. The electric conductivity meter includes temperature compensation mode and inner information logger for 200 time and temperature readings. The conductometer works with the Chinch connector for the Pt-1000 tempera-

ture sample.

A conventional cell equipped with a multiple inlet system for admission of solutions, purging and blanketing the solution with oxygen was used. The Zinc sheets were allowed to react with the solutions (HCl, NaOH, and NaCl) for at least 5 min and until a stable open circuit dissolution rate was obtained. The cell flow rate in each series of studies was roughly 3.0 ml/min. In the conductance process, a tiny volume flow cell is responsible for the response between the zinc sheets and solutions; following the values of electric conductivity, the response frequency is tracked by the flow cell moment.

# 3. Results and Discussion

To investigate zinc corrosion process and its inhibition by lignosulfonate, two different concentrations with three different corrosive media were selected. The results of these experiments are summarized in the following sections.

#### 3.1. Electrical Conductivity Measurements in HCl Solutions

When zinc sheet is immersed in HCl solution, it corrodes according to the following chemical reaction [13]:

$$Zn_{(s)} + 2H^{+}_{(aq)} + 2Cl^{-}_{(aq)} \rightarrow Zn^{2+}_{(aq)} + 2Cl^{-}_{(aq)} + H^{-}_{2(g)}$$
(1)

As shown in **Figure 2**, the value of electrical conductivity  $(mScm^{-1})$  of 1.00 M HCl solution containing zinc sheet decreases with the square root of time  $(min^{1/2})$ . Generally, the electrical conductivity depends on many factors like ionic charge and ionic mobility, in addition to the ionic concentration when dealing with molar conductivity. According to Equation (1), it is clear that  $Zn^{2+}$  ions replace H<sup>+</sup> ions, a comparison between the ionic molar conductivity of H<sup>+</sup>



**Figure 2.** The changes in electrical conductivity with time for zinc sheets immersed in 1.00 M HCl solutions in the presence of 0.0, 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS) at 20°C.

 $(\lambda_{H}^{+} = 349.65 \text{ Scm}^2 \cdot \text{mol}^{-1})$  and the ionic molar conductivity of  $\text{Zn}^{2+} (\lambda_{H}^{+1/2} \text{Zn}^{2+} = 52.8 \text{ Scm}^2 \cdot \text{mol}^{-1})$  [14] gives us an explanation of why this decrease in values of electrical conductivity with time of 1.00 M HCl solution that containing the zinc sheet.

As shown in **Figure 2**, the decrease in electrical conductivity with time is more pronounced in the solution of 1.00 M HCl without the addition of lignosulfonate is more pronounced in the compared to the solutions of 1.00 M HCl containing different concentrations of lignosulfonate (1.0, 10.0 and 20.0 mM), which is then converted into lignosulfonic acid in the acidic media that demonstrates a significant inhibition property in the corrosion process. To compare the slopes of the changes in electrical conductivity as a function of time between the different solutions, the electrical conductivity needs to be linearized so that the square root of time was used in the graphs instead of time.

The slope values of the changes of electrical conductivity of 1.00 M HCl solutions with and without lignosulfonate are listed in **Table 1**. The slope value was taken from the linear portion of the plot. The significant difference between the slope value of 1.00 M HCl solution without lignosulfonate (slope = -8.7071) and solutions containing 1.0, 5.0, 10.0 and 20.0 mM lignosulfonate indicates the inhibition behavior of lignosulfonate against the corrosion of zinc sheets in the 1.00 M HCl solution.

**Figure 3** shows the variation of electrical conductivity of 0.10 M HCl solutions in the presence and absence of lignosulfonate. In the figure, there are obvious differences between the decrease of electrical conductivity of 0.10 M HCl solutions containing zinc sheets in the presence of 0.0, 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate.

The slope values of the variation of electrical conductivity of 0.10 M HCl solutions with and without lignosulfonate are listed also in **Table 1**. As in the previous case, the obvious difference of the electrical conductivity-time slope value of the solution without the addition of lignosulfonate (slope = -0.5801) and, for instance, the solution containing 5.0 mM lignosulfonate (slope = -0.0064) indicates the inhibition property of lignosulfonate against the corrosion process in acidic medium. It is noticed that there were no systematic trends of variations in

**Table 1.** The slope values of changes of electrical conductivity in different solutions of 1.00 M and 0.10 M HCl containing zinc sheets and 0, 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS).

Solution description	Slope in 1.00 M HCl (mS·cm <sup>-1</sup> ·min <sup>-1/2</sup> )	Slope in 0.10 M HCl (mS·cm <sup>-1</sup> ·min <sup>-1/2</sup> )
0.0 mM LS	$-8.7071 \pm 0.2719$	$-0.5801 \pm 0.0093$
1.0 mM LS	$-0.1938 \pm 0.0073$	$-0.018 \pm 0.0014$
5.0 mM LS	$-0.2145 \pm 0.083$	$-0.064 \pm 0.0011$
10.0 mM LS	$-0.2725 \pm 0.0115$	$-0.0802 \pm 0.0008$
20.0 mM LS	$-0.0210 \pm 0.0130$	$-0.1309 \pm 0.0013$



**Figure 3.** The changes in electrical conductivity with time for zinc sheets immersed in 0.10 M HCl solutions in the presence of 0.0, 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS) at 20°C.

slopes with increasing the concentration of lignosulfonate. The ratio of the two slopes (e.g. without and with the addition of 5.0 mM lignosulfonate) for the 0.10 M HCl solutions is about 32 whereas in the case of 1.00 M HCl solutions at the same conditions the ratio is about 41, which is strongly indicates that the lignosulfonate works as a corrosion inhibitor for zinc metal and appears to be more effective in the stronger acidic solution with the same amount of lignosulfonate added.

Other information deduced from the above results are that the corrosion of zinc metal in 0.10 M HCl is weaker than that in 1.00 M HCl, which will be in a good agreement with the slope values of variation of electrical conductivity with time for the solutions of 1.00 M HCl and 0.10 M HCl (Table 1). This means that the conductivity measurement provides qualitative information about the strength of the corrosion process as well as the extent of the inhibition behavior. The addition of low concentrations of lignosulfonate (between 1.0 and 20.0 mM) does not lead to a significant change in the pH value or a critical increase of electrical conductivity readings of the corrosive solutions.

The corrosion tests of the electrical conduction method were very good in agreement with the corrosion loss tests of the sodium lignosulfonate inhibition property in HCl solution at 20°C. Which is strongly indicates that the lignosulfonate works as a corrosion inhibitor for zinc metal and appears to be more effective in the stronger acidic solution with the same amount of lignosulfonate added [9].

In acidic medium, the corrosion of zinc is effectively impacted by nitrogen, oxygen and sulfur-containing compounds [15] [16], and generally such compounds boost the hydrogen overvoltage of zinc metal which may, when it starts

to form a corrosive response of metal, be defined as the differentiation between hydrogen balance responses in solution and the hydrogen itself in solution [17]. The most common corrosion inhibitors are organic compounds that primarily contain nitrogen, sulfur or oxygen atoms and their structures are fitted with multiple bonds and aromatic rings [11] [18]-[23].

The Pourbaix diagram of zinc is shown in **Figure 4**. The diagram for zinc undergoes dissolution in acidic solutions (as  $Zn^{2+}$  ions) and in basic solutions (as zincate ions  $ZnO_2^{2-}$ ) as well as passivation of the zinc sheet as it is corroding in oxygenated alkaline solutions.

# 3.2. Electrical Conductivity Measurements in NaOH Solutions

When zinc sheet is immersed in NaOH solution, it corrodes according to the following chemical reaction [25]:

$$Zn_{(s)} + 2OH_{(aq)}^{-} \rightarrow ZnO_{2(aq)}^{2-} + H_{2(g)}$$
 (2)

We can present the general response mechanism in its easiest way as a series of two pseudo-elementary steps involving formation and dissolution of zinc hydroxide films [25]:

Film formation: 
$$\operatorname{Zn} + 2\operatorname{OH}^{-} \to \operatorname{Zn}(\operatorname{OH})_{2} + 2e^{-}$$
 (3)

Film dissolution:  $\operatorname{Zn}(\operatorname{OH})_{2} + \operatorname{xOH}^{-} \to \operatorname{Zn}(\operatorname{OH})_{2+x}^{x-}$  (4)

As shown in **Figure 5**, the value of electrical conductivity of NaOH solution containing zinc sheet decreases with time. According to chemical reaction (2), it is clearly that the total ionic electrical conductivities in the products side are less than that on the reactants side. The difference of electrical conductivity was unnoticeable between a solution of 1.00 M NaOH in the absence of lignosulfonate and solutions of 1.00 M NaOH in the presence of 1.0, 5.0, 10.0 and 20.0 mM lignosulfonate as shown in **Figure 5**.

As indicated in Table 2, all the slope values of the electrical conductivity



Figure 4. The Pourbaix diagram for zinc at room temperature (adopted from Ref. [24]).



**Figure 5.** The changes in electrical conductivity with time for zinc sheets immersed in 1.00 M NaOH solutions in the presence of 0.0, 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS) at 20°C.

**Table 2.** The slope values of changes of electrical conductivity in different solutions of 1.00 M and 0.10 M NaOH containing zinc sheets and 0.0, 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS).

Solution description	Slope in 1.00 M NaOH (mS·cm <sup>-1</sup> ·min <sup>-1/2</sup> )	Slope in 0.10 M NaOH (mS·cm <sup>-1</sup> ·min <sup>-1/2</sup> )
0.0 mM LS	$-0.2234 \pm 0.0051$	$-0.1621 \pm 0.0006$
1.0 mM LS	$-0.1075 \pm 0.0007$	$-0.1265 \pm 0.0007$
5.0 mM LS	$-0.2025 \pm 0.0022$	$-0.1152 \pm 0.0007$
10.0 mM LS	$-0.2011 \pm 0.0005$	$-0.1305 \pm 0.0004$
20.0 mM LS	$-0.1321 \pm 0.0009$	$-0.0921 \pm 0.0003$

changes with time of the solutions of 1.00 M NaOH with 1.0, 5.0, 10.0, and 20.0 mM lignosulfonate are less than in the case of 1.00 M NaOH without the addition of lignosulfonate.

**Figure 6** shows the changes in electrical conductivities of 0.10 M NaOH solutions containing zinc sheets with and without lignosulfonate. It is found that the corrosion process in this solution is weak as indicated by the slope values of the plots that show the variation of the electrical conductivity of these solutions with time (see **Table 2**). In this case, the corrosion inhibition behavior of lignosulfonate is less evident than in basic medium at 1.00 M NaOH due to the weakness of corrosion of zinc metal in 0.10 M NaOH solution. This weakness could be considered to the possibility of the passivation process of the zinc as shown in the Pourbaix diagram (**Figure 4**).

As indicated in **Table 2**, the difference in the slope values of the 0.10 M NaOH solution without lignosulfonate (slope = -0.2234) and the same solution containing



**Figure 6.** The changes in electrical conductivity with time for F immersed in 0.10 M NaOH solutions in the presence and absence of 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS) at 20.0 °C.

1.0 mM lignosulfonate (slope = -0.1075) indicates again the corrosion inhibition behavior of lignosulfonate.

The variation of electrical conductivities of corrosive media containing zinc sheets with and without inhibitor indicates the strength of the corrosion process and the inhibition behavior. The inhibition behavior of lignosulfonate will be evident if the corrosion is active so that in the case of testing 0.10 M NaOH as a corrosive medium, the inhibition behavior of lignosulfonate was less visible than in acidic medium.

#### 3.3. Electrical Conductivity Measurements in NaCl Solutions

**Figure 7** shows the variation of electrical conductivity of 5.0% (w/w) NaCl solutions in the presence and absence of lignosulfonate. As shown in this figure, the electrical conductivity of the solution without lignosulfonate decreases slightly or semi-constant with time, while the same solution with different concentrations of lignosulfonate, the electrical conductivity increases slightly with time. The slope values of the variation of electrical conductivity of 5.0% (w/w) NaCl solutions in the presence and absence of 1.0, 5.0, 10.0, and 20.0 mM of lignosulfonate with the time that are listed in **Table 3**. Because the slope value of electrical conductivity was less in case of presence of lignosulfonate than in case of absence of lignosulfonate, again we could notice the inhibition behavior of lignosulfonate.

**Figure 8** shows the variation of the electrical conductivity of 0.50% (w/w) NaCl solutions with and without lignosulfonate. As shown in **Figure 8**, the values of electrical conductivity of the NaCl solution containing zinc sheet were increasing with time. This increasing of electrical conductivity was due to the conversion of Zn to  $Zn^{2+}$ . In the case of NaCl solutions, there is no replacing of  $Zn^{2+}$ .



**Figure 7.** The changes in electrical conductivity with time for zinc sheets immersed in 5.0% (w/w) NaCl solutions in the presence and absence of 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS) at 20.0 °C.

**Table 3.** The slope values of changes of electrical conductivity in different solutions of 5.0% and 0.50% (w/w) NaCl containing zinc sheets and 0, 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonates (LS).

Solution description	Slope in 5.0% (w/w) NaCl (mS·cm <sup>-1</sup> ·min <sup>-1/2</sup> )	Slope in 0.50% (w/w) NaCl (mS·cm <sup>-1</sup> ·min <sup>-1/2</sup> )
0.0 mM LS	$0.287 \pm 0.0255$	$0.0114 \pm 0.0002$
1.0 mM LS	$0.1147 \pm 0.0029$	$0.0072 \pm 0.0003$
5.0 mM LS	$0.1650 \pm 0.0043$	$0.0087 \pm 0.0001$
10.0 mM LS	$0.0346 \pm 0.0014$	$0.0072 \pm 0.0001$
20.0 mM LS	$0.0391 \pm 0.0020$	$0.0082 \pm 0.0001$



**Figure 8.** The changes in electrical conductivity with time for zinc sheets immersed in 0.50% (w/w) NaCl solutions in the presence and absence of 1.0, 5.0, 10.0 and 20.0 mM of lignosulfonate (LS) at 20.0 °C.

ions with  $H^+$  as occurring in the acidic medium or with  $OH^-$  as occurring in the basic medium.

The slope values of the change of electrical conductivity of 0.50% (w/w) NaCl solutions with and without lignosulfonate are listed in **Table 3**. Again, the difference of the slope values of the solution without lignosulfonate (slope = 0.0114) and, for instance, the solution contains 1.0 mM lignosulfonate (slope = 0.0072) indicates the inhibition property of lignosulfonate against the corrosion process in the salt medium.

The inhibition behavior of lignosulfonate is already affirmed [6] [9], but the new in this study that HCl (1.00 M and 0.10 M), NaOH (1.00 M and 0.10 M) and NaCl solution (5.0% and 0.50% w/w) were tested as corrosive media. A result from this study tests the electrical conductivity method to be a simple monitoring tool of corrosion and corrosion inhibition processes.

#### 4. Conclusions

This study succeeds in using the electrical conductivity method as a new monitoring tool to provide qualitative information about the strength of corrosion as well as the extent of the inhibition behavior. The variation of electrical conductivity readings of three different corrosive media containing zinc sheets in the absence and presence of four different concentrations of lignosulfonate indicates the inhibition behavior of lignosulfonate in the three selected corrosive media. The inhibition behavior of lignosulfonate was very pronounced in acidic medium and less visible in a basic medium (0.10 M NaOH) and neutral medium (0.50% NaCl).

Suggested additional work is making electrical conductivity measurements at other values of temperature and making measurements on the surface of zinc sheets by scanning electron microscope coupled with an energy-dispersive system.

### Acknowledgements

This work was supported by Petra University. The technical assistance of Mr. Mustafa Mohamad and Miss Ala' Qutaishat is highly acknowledged.

#### **Conflicts of Interest**

The authors declare no conflicts of interest regarding the publication of this paper.

#### References

- Baboian, R. (2005) Corrosion Tests and Standards: Application and Interpretation. 2nd Edition, ASTM international, West Conshohocken, 1. https://doi.org/10.1520/MNL20-2ND-EB
- Freeman, R.A. and Silverman, D.C. (1992) Technical Note: Error Propagation in Coupon Immersion Tests. *Corrosion*, 48, 463-466. https://doi.org/10.5006/1.3315961
- [3] Yang, L. (2008) Techniques for Corrosion Monitoring. Woodhead Publishing, Cam-

bridge, 149. https://doi.org/10.1533/9781845694050

- [4] Gray, J.R. (2004) Conductivity Analyzers and Their Application. In: Down, R.D. and Lehr, J.H., Eds., *Environmental Instrumentation and Analysis Handbook*, Wiley, New York, 491. <u>https://doi.org/10.1002/0471473332.ch23</u>
- [5] Landolt, D. and Mischler, S. (2011) Tribocorrosion of Passive Metals and Coatings. Woodhead Publishing Limited, Oxford, Philadelphia. https://doi.org/10.1533/9780857093738
- [6] Celis, J.P. and Ponthiaux, P. (2012) Testing Tribocorrosion of Passivating Materials Supporting Research and Industrial Innovation. In: *Handbook EFC* 62, Maney Pub, Leeds, UK.
- [7] Montemor, M.F., Simões, A.M.P. and Ferreira, M.G.S. (2003) Chloride-Induced Corrosion on Reinforcing Steel: From the Fundamentals to the Monitoring Techniques. *Cement and Concrete Composites*, 25, 491-502. https://doi.org/10.1016/S0958-9465(02)00089-6
- [8] Berradja, A. (2018) Metallic Glasses for Triboelectrochemistry Systems, Chapter 5. In: Huang, H., Ed., *Metallic Glasses-Properties and Processing*, Intech Open, London, UK. <u>https://doi.org/10.5772/intechopen.78233</u>
- [9] Altwaiq, A., Abdel-Rahem, R., Alshamaileh, E., Al-luaibi, S. and Khouri, S. (2015) Sodium Lignosulfonate as a Friendly-Environment Corrosion Inhibitor for Zinc Metal in Acidic Media. Eurasian *Journal of Analytical Chemistry*, **10**, 10-18.
- [10] Frankel, G.S. and Landolt, D. (2007) Kinetics of Electrolytic Corrosion. In: *Ency-clopedia of Electrochemistry*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany.
- [11] Ouyang, X., Qiu, X., Lou, H. and Yang, D. (2006) Corrosion and Scale Inhibition Properties of Sodium Lignosulfonate and Its Potential Application in Recirculating Cooling Water System. *Industrial and Engineering Chemistry Research*, 45, 5716-5721. https://doi.org/10.1021/ie0513189
- [12] Jones, D.A. (1992) Principles and Prevention of Corrosion. Macmillan, New York.
- [13] Prabhu, R.A., Venkatesha, T.V. and Praveen, B.M. (2012) Electrochemical Study of the Corrosion Behavior of Zinc Surface Treated with a New Organic Chelating Inhibitor. *ISRN Metallurgy*, 2012, 1-7. https://doi.org/10.5402/2012/940107
- [14] Laidler, K.J., Meiser, J.H. and Sanctuary, B.C. (2003) Physical Chemistry. 4th Edition, Houghton Mifflin Co, Boston, 291.
- [15] Manov, S., Noli, F., Lamazouere, A.M. and Aries, L. (1999) Surface Treatment for Zinc Corrosion Protection by a New Organic Chelating Reagent. *Journal of Applied Electrochemistry*, 29, 995-1003. <u>https://doi.org/10.1023/A:1003585816876</u>
- [16] Hinton, B.R.W. and Wilson, L. (1989) The Corrosion Inhibition of Zinc with Cerous Chloride. *Corrosion Science*, 29, 967-985. https://doi.org/10.1016/0010-938X(89)90087-5
- [17] MacInnes, D.A. and Aldler, L. (1919) Hydrogen Overvoltage. *Journal of the Ameri*can Chemical Society, **41**, 194-207. <u>https://doi.org/10.1021/ja01459a006</u>
- [18] Abdallah, M., Zaafarany, I., Al-Karanee, S.O. and Abd El-Fattah, A.A. (2012) Antihypertensive Drugs as an Inhibitors for Corrosion of Aluminum and Aluminum Silicon Alloys in Aqueous Solutions. *Arabian Journal of Chemistry*, 5, 225-234. https://doi.org/10.1016/j.arabjc.2010.08.017
- [19] Fouda, A.S., Abdallah, M. and Eissa, M. (2013) Corrosion Inhibition of Aluminum in 1 M Phosphoric Acid Solutions Using Some Chalcones Derivatives and Synergistic Action with Halides Ions. *African Journal of Pure and Applied Chemistry*, 7,

394-404.

- [20] Oguzie, E.E., Onuoha, G.N. and Ejike, E.N. (2007) Effect of Gongronema Latifolium Extract on Aluminium Corrosion in Acidic and Alkaline Media. *Pigment and Resin Technology*, **36**, 44-49. <u>https://doi.org/10.1108/03699420710718751</u>
- [21] El Nemr, A., Moneer, A.A., Khaled, A., El Sikaily, A. and El-Said, G.F. (2014) Modeling of Synergistic Halide Additives Effect on the Corrosion of Aluminium in Basic Solution Containing Dye. *Materials Chemistry and Physic*, **144**, 139-154. https://doi.org/10.1016/j.matchemphys.2013.12.034
- [22] El-Etre, A.Y., Megahed, H.E., Abdallah, M. and Obeid, M.A. (2004) The Effect of Cationic Surfactants on the Corrosion of Aluminum in Oxalic Acid. *Corrosion Prevention and Control*, 51, 23-29.
- [23] Abdallah, M. (2000) Tetradecyl-1,2-Diol Propenoxylates as Inhibitors for Corrosion of Aluminum in Hydrochloric Acid. *Bulletin of Electrochemistry*, **16**, 258-263.
- [24] Delahay, P., Pourbaix, M. and Rysselberghe, P. (1951) Potential-pH Diagram of Zinc and Its Applications to the Study of Zinc Corrosion. *Journal of the Electrochemical Society*, 98, 101-105. https://doi.org/10.1149/1.2778110
- [25] Mokaddem, M., Volovitch, P. and Ogle, K. (2010) The Anodic Dissolution of Zinc and Zinc Alloys in Alkaline Solution. I. Oxide Formation on Electrogalvanized Steel. *Electrochimica Acta*, 55, 7867-7875. https://doi.org/10.1016/j.electacta.2010.02.020