

A STUDY ON PRASEODYMIUM 4-HYDROXYCINNAMATE AS AN INHIBITOR FOR CARBON STEEL IN FRESH COOLING WATER SYSTEM OF CA MAU FERTILIZER PLANT

D. T. Ngan¹, L. T. Dai^{1,2}, P. M. Q. Binh^{1,*}, M. Vaka³, N. D. Nam^{1,*}

¹*Petrovietnam University, 762 Cach Mang Thang Tam Street, Ba Ria City, Ba Ria - Vung Tau Province, Vietnam*

²*Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan 609-735, Republic of Korea*

³*School of Life and Environmental Sciences, Deakin University, Victoria 3220, Australia*

*Email: binhpmq@pvu.edu.vn and namnd@pvu.edu.vn

Received: 1 August 2017; Accepted for publication: 8 October 2017

ABSTRACT

Praseodymium 4-hydroxycinnamate compound has been successfully studied as an effective corrosion inhibitor for carbon steel in 0.1 M NaCl solution using electrochemical techniques and surface analysis. The results of electrochemical techniques indicated that there were the decrease of current density and the appearance of protective film on the steel surface evidencing the presence of inhibitor and the effect of Pr(4OHCin)₃ compound depending on its concentration in solution. The surface analysis show a confirmation of the protective film formation which is a result of adsorption between the metal and inhibitor components. In addition, inhibition performance of Pr(4OHCin)₃ compound is also compared to the inhibition performance of TRACT 109, which has been added to a fresh cooling water system of Ca Mau fertilizer plant.

Keywords: Ca Mau fertilizer plant; fresh cooling water system; carbon steel; corrosion inhibitor; Praseodymium 4-hydroxycinnamate

1. INTRODUCTION

Carbon steel structures can be easily corroded in many applications, such as pipelines and/or tanks under various conditions with neutral pH in the air or low pH in a CO₂ atmosphere or evenly in seawater [1 - 4] containing large amounts of chloride ions which is the cause of the growth of the pit by autocatalytic mechanism [5]. Pitting corrosion is one of the forms of extremely localized attack causing holes in a metal, especially in chloride solution [6, 7], which is often difficult to detect and becomes an insidious destructive process because of the small size of the pits and the coating of corrosion products [8]. To illustrate, the first step of the anodic dissolution of Fe in chloride solutions is the formation of passive oxide layer Fe_xO_y/Fe(OH)_y,

covering the surface of the steel [9] to prevent contacting directly to the corrosion environment, according to the reaction (1, 2). However, the passivating film is likely to be weaker and the potential difference between the layer and the defect in the steel surface increases, due to the mechanical damage of the film [10], caused by stress or particles of a second phase and therefore, the initial pits were formed.



The pits gain positive electrical charge in contrast to the electrolyte surrounding the pits which attract negative ion of chloride increasing acidity of the electrolyte [11]. For this reason, the presence of chloride ion in the solution leads to the increasing of the corrosion acceleration as well as the corrosion rate [12]. In the case of the presence of the corrosion inhibitor, negatively charged inhibitor molecules interact with positively charged metal surface form a protective film and the growth of the pits, as well as the corrosion rate of steel, are reduced [13]. Thereby, using inhibitor [14 - 16] should be the best approach to mitigate corrosion and enhance the lifetimes of such expensive infrastructure. Many investigations have been developing a range of inhibitors based on chromate, carboxylate compounds, imidazoline and its derivatives [17 - 20] that best suit applications because the application of adsorption or protective layer [21] formed on the metal surface is to increase the corrosion resistance which plays a significant role in minimizing the cost and reducing the toxic effect. However, ion chromates and molybdates are toxic materials and effect to the environment, human health [22 - 25]. Furthermore, imidazoline and their derivatives are typical examples of safe, effective organic corrosion inhibitors. But imidazoline and their derivatives have been found to aggravate localized corrosion [26] in the presence of chloride environments due to the formation of a small number of major anodes, resulting in highly concentrated anodic dissolution. Therefore, it leads to a serious investigation for new, more efficient, localized and environmentally benign inhibitor systems. In this study, praseodymium 4-hydroxycinnamate [27 - 29] has been studied as an effective corrosion inhibitor for carbon steel in 0.1 M NaCl solution. In addition, TRACT 109, which has been added to a fresh cooling water system of Ca Mau fertilizer plant, is also used for comparison.

2. EXPERIMENTAL

Experiments were carried out at room temperature and used praseodymium 4-hydroxycinnamate - $\text{Pr}(\text{4OHCin})_3$ - and TRACT 109 as the corrosion inhibitors in 0.1 M NaCl solution. TRACT 109 with main nitrite component was supplied by Ca Mau fertilizer plant and $\text{Pr}(\text{4OHCin})_3$ can be found in the previous publication [28]. In this study, $\text{Pr}(\text{4OHCin})_3$ and TRACT 109 were added to 0.1 M NaCl solutions using reagent grade sodium chloride purchased from Sigma Aldrich, distilled water, and 12 hours of stirring with the concentration of 0, 100, 300 and 600 ppm of $\text{Pr}(\text{4OHCin})_3$, while TRACT 109 with the concentration of 1500, 2000, 2400, and 3000 ppm, where Ca Mau fertilizer plant has been using the range of concentration from 2000 to 2400 ppm. The working electrodes used for the electrochemical tests were made from carbon steel with the dimension of 10 mm × 10 mm × 3 mm which were mounted by epoxy resin according to ASTM G5-94 standard. The surface of samples was abraded by sand paper with different roughness and this process change direction every 90° for every changing roughness. The samples were immersed in 0.1 M NaCl solution containing inhibitors at different concentration for 24 h to prepare for the electrochemical tests. SP 300 system (Biologic Scientific Instruments) with a commercial software program for AC measurements was used to

conduct these tests. The electrochemical impedance spectroscopy (EIS) test showed the resistance of the protective film and the impedance of the double layer of charge between the protective layer and the substrate surface and then determined the efficiency of inhibitor. The EIS has carried out the performance of the steels from 10 kHz to 10 MHz with a peak-to-peak amplitude at 10 mV. Furthermore, potentiodynamic polarization tests were carried out by using a silver/silver chloride (Ag/AgCl) as the reference electrode and a counter electrode made of titanium. The sweeping potential range of the electrodes was from an initial potential of -250 mV to anodic potential with every step of 0.166 mV/s. Scanning electron microscopy (SEM) was used to evaluate the effect of inhibitor the steel surface after immersion for 24 hours in 0.1 M NaCl solution, especially the appearance of the pits in uninhibited system. The method used JOEL mechanic at 20 kV and with a magnification of 500 times. In addition, the surface film was also examined by X-ray diffraction using X'Pert Powder at the voltage of 45 kV and the current of 40 mA. The range of 2θ angle is from 10 to 100° at a rate of 0.02° .

3. RESULTS AND DISCUSSION

Figure 1 shows the potentiodynamic polarization curves of carbon steel without and with TRACT 109 and Pr(4OHcin)₃ addition in 0.1 M NaCl solution with various concentrations. The increase of inhibitor concentration leads to the decrease of current density, suggesting an improvement of inhibition performance. In addition, the results indicated that there was a protective film constructed on the steel surfaces immersed in solutions containing inhibitors. The current densities were lower than that of the result of uninhibited system, where a passivation region had formed and there was no pitting observed up to 0 mV_{Ag/AgCl}. Whereas, carbon steel immersed in 0.1 M NaCl solution showed pitting corrosion due to a rapid increase in current density. Interestingly, lower passive current density and the wider range of passive potential in the results of steel immersed in 0.1 M NaCl solution containing Pr(4OHcin)₃ compound were performed in comparison with that of the result of steel immersed in 0.1 M NaCl solution containing TRACT 109, suggesting higher inhibition performance and pitting inhibition. In addition, lower passive current density and the wider range of the passive potential were noticed to an increase of Pr(4OHcin)₃ compound concentration up to 300 ppm, whereas the current density performed in 600 ppm slightly increased in contrast to 300 ppm. The same trend has been observed on TRACT 109 system up to 2000 ppm. The reason for this phenomenon is that the high inhibitor concentration slowed down the ion movement in the solution, preventing the adsorption onto the steel surface. Thereby, 300 ppm of Pr(4OHCin)₃ and 2000 ppm of TRACT 109 suggested the most effective corrosion inhibition of carbon steel in 0.1 M NaCl solution.

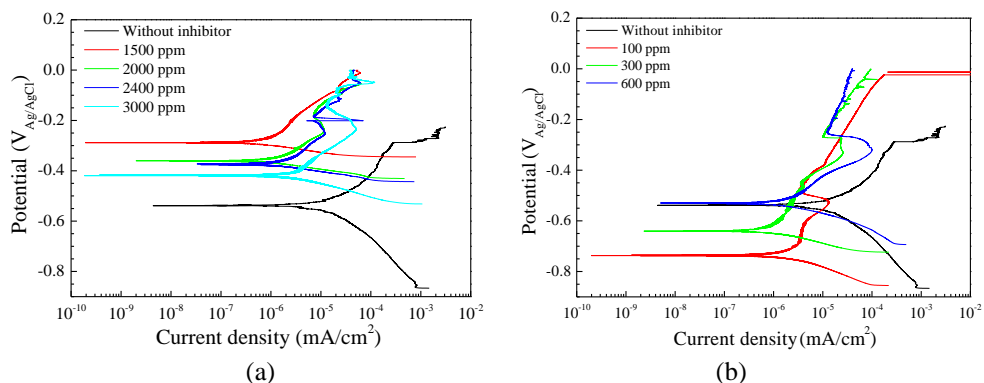


Figure 1. Potentiodynamic polarization curves of carbon steel after 24 h immersion in solutions containing (a) TRACT 109 and (b) Pr(4OHCin)₃.

Table 1. Corrosion properties from the potentiodynamic polarization curves of carbon steel after 24 h immersion in solutions.

| Concentration (ppm) | E_{corr} (mV _{Ag/AgCl}) | i_{corr} (nA/cm ²) | β_a (V/decade) | $-\beta_c$ (V/decade) | Inhibition efficiency ($\eta\%$) |
|-------------------------------|--|---|----------------------|-----------------------|------------------------------------|
| TRACT 109 | | | | | |
| 0 | -538 | 25.11 | 0.204 | 0.208 | - |
| | -538 | 23.15 | 0.202 | 0.205 | - |
| | -535 | 24.22 | 0.205 | 0.206 | - |
| Average | -537 | 24.16 | | | - |
| 1500 | -291 | 0.53 | 0.083 | 0.029 | 97.84 |
| | -290 | 0.52 | 0.082 | 0.030 | 97.85 |
| | -286 | 0.52 | 0.084 | 0.029 | 97.85 |
| Average | -289 | 0.52 | | | 97.84 |
| 2000 | -354 | 0.412 | 0.016 | 0.025 | 98.28 |
| | -356 | 0.411 | 0.019 | 0.027 | 98.29 |
| | -357 | 0.410 | 0.018 | 0.028 | 98.29 |
| Average | -356 | 0.411 | | | 98.29 |
| 2400 | -372 | 0.796 | 0.045 | 0.026 | 96.68 |
| | -374 | 0.795 | 0.044 | 0.027 | 96.69 |
| | -373 | 0.797 | 0.046 | 0.027 | 96.68 |
| Average | -373 | 0.796 | | | 96.68 |
| 3000 | -424 | 1.9 | 0.120 | 0.050 | 92.08 |
| | -426 | 2.0 | 0.117 | 0.052 | 91.67 |
| | -422 | 2.1 | 0.115 | 0.049 | 91.25 |
| Average | -424 | 2.0 | | | 91.67 |
| Pr(4OHCin)₃ | | | | | |
| 100 | -735 | 1.01 | 0.092 | 0.044 | 95.79 |
| | -737 | 1.01 | 0.089 | 0.043 | 95.79 |
| | -733 | 0.98 | 0.090 | 0.045 | 95.92 |
| Average | -735 | 1.00 | | | 95.83 |
| 300 | -643 | 0.27 | 0.079 | 0.027 | 98.89 |
| | -639 | 0.27 | 0.077 | 0.025 | 98.90 |
| | -638 | 0.27 | 0.080 | 0.028 | 98.89 |
| Average | -640 | 0.27 | | | 98.89 |
| 600 | -527 | 0.95 | 0.049 | 0.041 | 96.06 |
| | -525 | 0.94 | 0.051 | 0.040 | 96.08 |
| | -532 | 0.93 | 0.055 | 0.041 | 96.08 |
| Average | -528 | 0.94 | | | 96.08 |

Table 1 shows the corrosion properties of the samples and the inhibitor efficiency ($\eta\%$) was determined from the curves using the following equation (3):

$$\eta = \frac{i_{corr}^o - i_{corr}}{i_{corr}^o} \times 100\% \quad (1)$$

where η is the inhibition performance, i_{corr} and i_{corr}^o are the corrosion current density in the presence and absence of the inhibitor, respectively. The current density values were calculated by Tafel methods and the highest inhibition efficiency was reached at 300 ppm of $\text{Pr}(\text{4OHCin})_3$ with 98.89 % and 2000 ppm of TRACT 109 with 98.29 %.

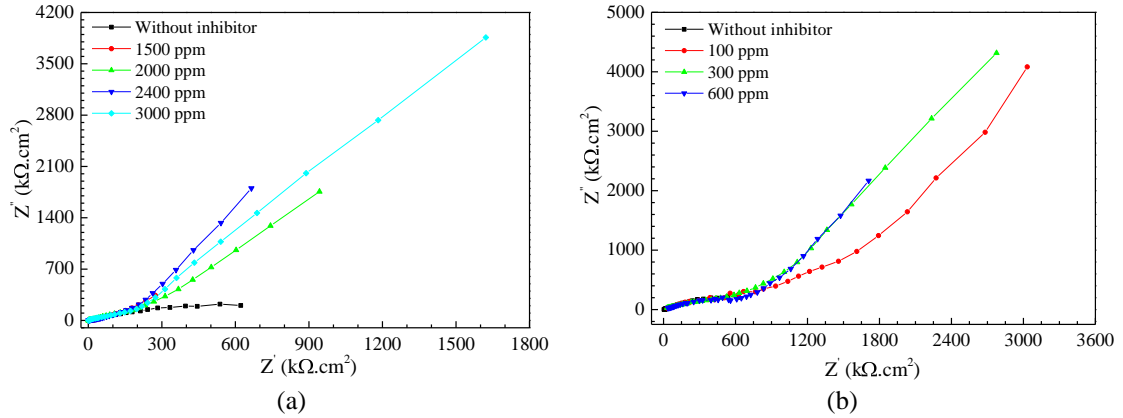


Figure 2. Nyquist plots of carbon steel after 24 h immersion in solutions containing (a) TRACT 109 and (b) $\text{Pr}(\text{4OHCin})_3$.

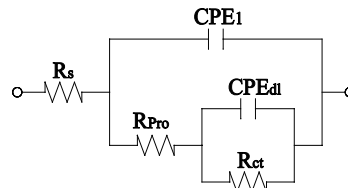


Figure 3. Physical model for simulating an equivalent circuit to fit the EIS data (R_{rust} is replaced by R_{pro} in the case of inhibition system).

Table 2. Fitting results of EIS data for carbon steel after 24 h immersion in solutions.

| Concentration (ppm) | R_s ($\Omega \cdot \text{cm}^2$) | CPE_1 | | R_{pro} ($\Omega \cdot \text{cm}^2$) | CPE_{dl} | | R_{ct} ($\Omega \cdot \text{cm}^2$) |
|------------------------------|--------------------------------------|---------------------------------|---------|--|---------------------------------|---------|---|
| | | C ($\mu\text{F}/\text{cm}^2$) | n (0~1) | | C ($\mu\text{F}/\text{cm}^2$) | n (0~1) | |
| TRACT 109 | | | | | | | |
| 0 | 1697 | 0.050 | 0.7096 | 0.7E4 | 3.294 | 0.5758 | 1.08E6 |
| 1500 | 1669 | 0.024 | 0.7410 | 2.4E5 | 2.065 | 0.7021 | 3.61E7 |
| 2000 | 1639 | 0.013 | 0.7534 | 3.6E5 | 1.296 | 0.7744 | 5.38E7 |
| 2400 | 1613 | 0.034 | 0.7388 | 1.8E5 | 2.365 | 0.6897 | 2.69E7 |
| 3000 | 1589 | 0.048 | 0.7103 | 8.1E4 | 3.022 | 0.6001 | 1.19E7 |
| $\text{Pr}(\text{4OHCin})_3$ | | | | | | | |
| 100 | 1599 | 0.036 | 0.7234 | 1.6E5 | 2.211 | 0.7512 | 2.39E7 |
| 300 | 1555 | 0.011 | 0.8680 | 7.2E5 | 0.987 | 0.9011 | 10.8E7 |
| 600 | 1521 | 0.032 | 0.7366 | 1.9E5 | 2.109 | 0.7665 | 2.76E7 |

Figure 2 presents the EIS results in the Nyquist formats obtained from the carbon steel after 24 h immersion in solutions containing TRACT 109 and $\text{Pr}(\text{4OHCin})_3$ corrosion inhibitors. Fig.

2(a) shows the impedance spectra of steel immersed in solutions containing TRACT 109, additionally, Fig. 2(b) presents the impedance spectra of steel immersed in solutions containing Pr(4OHCin)₃. In EIS spectra, the high frequency spectra shows the local surface defects, the medium frequency spectra are related to the processes within the protective film, and the low frequency spectra indicate the processes at the metal/ protective film interface, respectively. The impedance spectra clearly indicated that the impedance value increased with an increase of inhibitor concentration up to 2000 ppm for TRACT 109 and 300 ppm for Pr(4OHCin)₃ and then decreased when more inhibitors added to the solution, suggesting that the electrochemical behavior of steel has been strongly influenced by type of inhibitor and concentration. The results also showed two-time constants related to the whole concentrations, resulting the formation of the rust on the steel surface in uninhibited system or protective layer on the steel surface for inhibited systems. The greater inhibition performance was demonstrated in the potentiodynamic polarization results presented above in this paper. In the absence of kinetic models, it is known that equivalent circuit models derived from EIS data could be used to propose inhibition processes and mechanisms. Based on the electrochemical data and surface analysis, the equivalent circuits shown in Fig. 3 was selected for fitting the EIS data using the Zsimpwin program. In this case, R_s indicates the solution resistance, CPE_1 and CPE_{dl} are the constant phase elements of the protective film and double layer, R_{Pro} and R_{ct} represent the protective film and charge transfer resistances, respectively. The Fig. 3 also indicated that R_{Pro} and protective layer should be replaced by R_{rust} and rust layer for steel immersed in uninhibited systems. To improve the fitting quality, the capacitor could be replaced by a CPE. Additionally, the CPE for both protective film/rust and double layer contains a capacitance (C) and phenomenological coefficient (n).

The optimized values of the electrochemical parameters of fitting EIS data are given in Table 2. Fitting results indicated that the protective and double layer resistances were increased with an increase of inhibitor concentration up to 2000 ppm for TRACT 109 and 300 ppm for Pr(4OHCin)₃ and then decreased when more inhibitors were added to the solution. Whereas, the protective and double layer capacitances performed the same trend with resistances, suggesting that 2000 and 300 ppm are the optimal concentrations for mitigating corrosion of steel in 0.1 M NaCl solution in this study. This is very important because higher R_{Pro} and R_{ct} relate to the exchange current density of the Fe/Feⁿ⁺ system, indicating good inhibition performance. Additionally, lower C_1 and C_{dl} can be attributed to the entire covered surface via the barrier film with lower pore density, improved compatibility, adhesion of barrier layer on the steel surface, resulting in higher corrosion inhibition. The EIS results are in correspondence with potentiodynamic polarization above and surface analysis below.

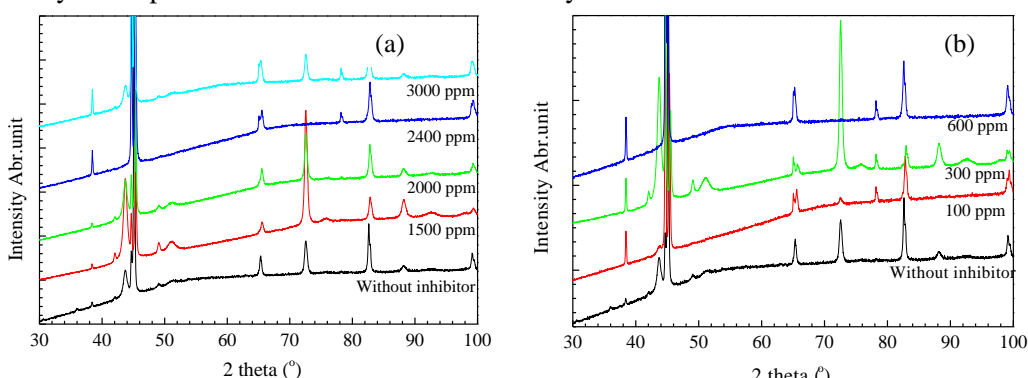


Figure 4. XRD analysis for steel surface after 24-hour immersed in NaCl 0.1 M without and with (a) TRACT 109 and (b) Pr(4OHCin)₃ inhibitors.

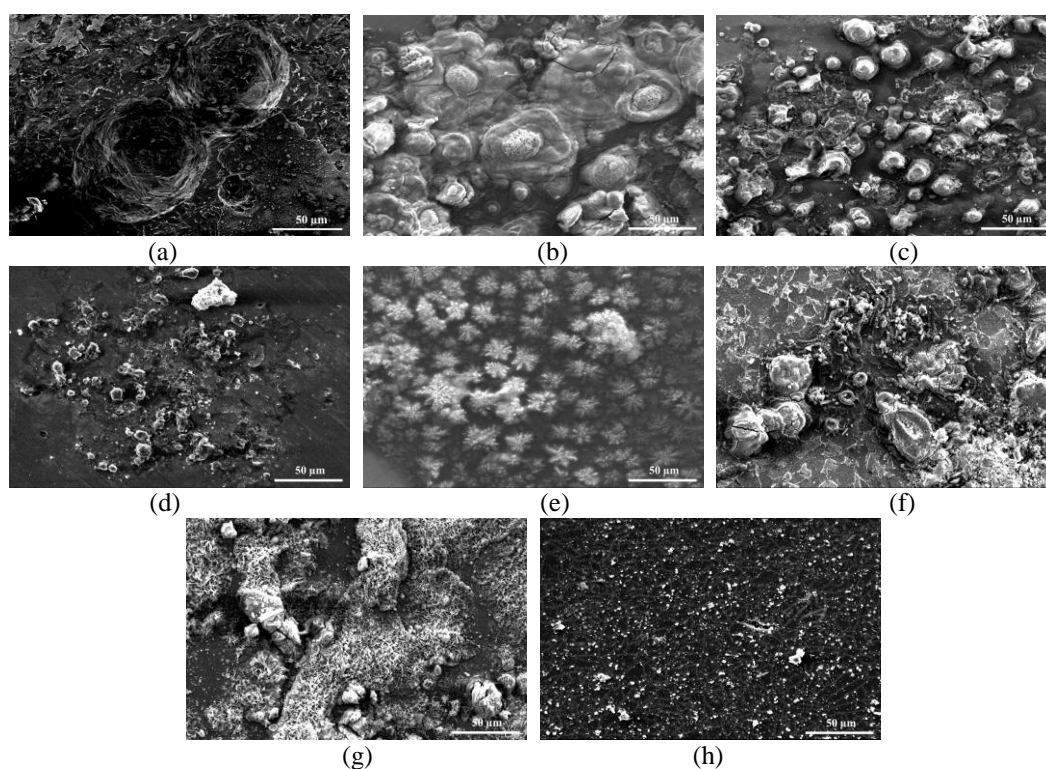


Figure 5. SEM images of carbon steel surfaces after 24 h immersion in 0.1 M NaCl solutions (a) without inhibitor addition, with (b) 1500, (c) 2000, (d) 2400, and (e) 3000 ppm TRACT 109 and (f) 100, (g) 300, and (h) 500 ppm Pr(4OHcin)₃ inhibitors.

The results of X-ray diffraction analysis of steel samples after immersion in chloride solution with the presence and absence of the inhibitors shown in Fig. 4, and were analyzed by the JCPDF-ICDD software (Joint Committee on Powder Diffraction International Centre for Diffraction Data). The results show there are phase {103} around 38.4°, phase {110} around 43.7°, phase {330} around 65.1°, phase {330} around 72.5°, phase {510} around 78.2°, and phase {521} around 88.1°. These positions indicate that iron products are in the form of Fe_xO_y and Fe(OH)_y, which combined with the product of the adsorption of the inhibitor on the steel surface to make the firmly protective layer attaching to the steel surface. The results observe the increase of corrosion resistance of steel when working in the solution. Figure 5 shows the SEM images of steel surfaces after 24 h immersion in 0.1 M NaCl solutions (a) without inhibitor addition, with (b) 1500, (c) 2000, (d) 2400, and (e) 3000 ppm TRACT 109 and (f) 100, (g) 300, and (h) 500 ppm Pr(4OHcin)₃ inhibitors. The results indicated that a significant difference of surface morphologies was observed on steel surface due to the pitting corrosion. Both pitting corrosion and severe corrosion attack outside the pit were observed on the steel surface immersed in 0.1 M NaCl solution without any inhibitor additions due to the inward penetration of Cl⁻ as shown in Fig. 5(a). While no pitting was observed on the steel surface immersed in the solutions containing TRACT 109 and Pr(4OHcin)₃ inhibitors as shown in Fig. 5(b-h). It suggested that TRACT 109 and Pr(4OHcin)₃ additions inhibited not only localized corrosion but also severe general corrosion of carbon steel in 0.1 M NaCl solutions.

The investigated results indicated that the corroded surface after 24-hour immersion in NaCl 0.1 M solution without and with inhibitor at various concentration. The initial pitting

indicated that significant corrosion occurred and lots of corroded productions on the steel surface in solution without inhibitor addition. It is observed the result of a large amount of gas bubbles generated due to the soluble reaction of iron. In contrast, the presence of inhibitor in the solution limited attack and the protective layer formed on the surface, which was suggested to be the main mechanism of corrosion inhibition. At the right time immersed steel sample in the solution containing inhibitor, the density of ions Fe^{n+} around the defects was quite high cause the attractions of anionic groups (NO_2^- and 4OHCin^-) which is a part of the inhibitor to form a local protective layer in the defect site, consequently resulting in controlling the localized corrosion. It is suggested that the potential of the local protection was different from those of the steel surface and the corrosion and the inhibitor process were continuing lead to the growth of the local protective layer. Furthermore, Pr^{3+} could be hydrolyzed to form $\text{Pr}(\text{OH})_3$ and Pr_2O_3 , forming a thin protective layer on the surface beside the local protection layer. This is attributed to higher inhibition performance of $\text{Pr}(4\text{OHCin})_3$ compound in comparison with TRACT 109.

4. CONCLUSIONS

Mixed inhibition of carbon steel was achieved using the $\text{Pr}(4\text{OHCin})_3$ compound. Electrochemical characterization confirmed the mixed inhibition mechanism, as well as demonstrating the synergism of the two Pr^{3+} and 4OHCin^- components of the inhibitor complex. Surface characterization combined with electrochemical results confirmed the presence of the inhibitor on the steel surface and provided some information on the deposition mechanism that slows down the active surface area. The efficient corrosion inhibition of carbon steel in a fresh cooling water system of Ca Mau fertilizer plant by this $\text{Pr}(4\text{OHCin})_3$ compound at low concentrations is promising as the search to find viable alternatives to TRACT 109, which showed lower inhibition performance at higher concentrations, and toxic Cr(VI) technologies continues.

Acknowledgement. This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 104.06-2016.08. The author is also grateful for the support of Vietnam Oil & Gas Group and PetroVietnam University.

REFERENCES

1. Iannuzzi M., Barnoush A., Johnsen R. - Materials and corrosion trends in offshore and subsea oil and gas production, *npj Materials Degradation* **1** (1) (2017) 1-11.
2. Hou B., Li X., Ma X. - The cost of corrosion in China, *npj Materials Degradation* **1** (4) (2017) 1-10.
3. Nam N. D., Bui Q.V ., Mathesh M., Tan M. Y. J., Forsyth M. - A study of 4-carboxyphenylboronic acid as a corrosion inhibitor for steel in carbon dioxide containing environments, *Corros. Sci.* **76** (2013) 257-266.
4. Song Y., Jiang G., Chen Y., Zhao P., Tian Y. - Effects of chloride ions on corrosion of ductile iron and carbon steel in soil environments, *Sci. Rep.* **7** (2017) 1-12.
5. Jones D.A. - Principle and prevention of corrosion, Prentice Hall Inc.: Upper Saddle River, 1996.
6. Nam N. D., Kim M. J., Jang Y. W., Min J. G. - Effect of tin on the corrosion behavior of low-alloy steel in an acid chloride solution, *Corros. Sci.* **52** (2010) 14-20.
7. Burstein G. T. - Revealing corrosion pits, *Nature* **350** (1991) 188-189.

8. Scully J. C. - Corrosion: Aqueous processes and passive films, Academic Press, 1989.
9. Ameer M. A., Fekry A. M., Ghoneim A. A., Attaby F. A. - Electrochemical corrosion inhibition of steel in alkaline chloride solution, *Int. J. Electrochem. Sci.*, **5** (2010) 1847-1861.
10. Riskin J. - Electrocorrosion and protection of metals, Elsevier Science, 2008.
11. Ma F. Y. - Corrosive effects of chlorides on metals, InTechOpen, 2012.
12. McCafferty E. - Validation of corrosion rates measured by the Tafel extrapolation method, *Corros. Sci.* **47** (2015) 3202-3215.
13. Dariva C. G., Galio A. F. - Corrosion inhibitors - Principles, mechanisms and applications, InTechOpen, 2014.
14. Flick E. W. - Corrosion inhibitors: An industrial guide, 1st edition, Noyes Pubns, 1987.
15. Finšgar M., Jackson J. - Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review, *Corros. Sci.* **86** (32014) 17-41.
16. Ahmad Z. - Principles of corrosion engineering and corrosion control, Butterworth-Heinemann, 2006.
17. Qi J. T., Hashimoto T., Walton J. R., Zhou X., Skeldo P. - Trivalent chromium conversion coating formation on aluminium, *Surf. Coat. Technol.* **280** (2015) 317-329.
18. Bentiss F., Traisnel M., Lagrenee M. - The substituted 1,3,4-oxadiazoles: a new class of corrosion inhibitors of mild steel in acidic media, *Corros. Sci.* **42** (2000) 127-146.
19. Anderson E.B., Long T.E. - Imidazole- and imidazolium-containing polymers for biology and material science applications, *Polymer* **52** (2010) 2447-2454.
20. Jovancicevic V. - Inhibition of carbon dioxide corrosion of mild steel by imidazolines and their precursors, *Corrosion* **55** (1999) 449-455.
21. Montemor M. F. - Functional and smart coatings for corrosion protection: A review of recent advances, *Surf. Coat. Technol.* **258** (2014) 17-37.
22. Urben P., Bretherick's Handbook of Reactive Chemical Hazards, Elsevier, 2017.
23. Kanematsu H., Barry D. M. - Corrosion control and surface finishing: Environmentally friendly approaches, Springer, 2016.
24. Buchanan R.T. - The full list of 116 things that cause cancer, Independent News, 2015.
25. Bethencourt M., Botana F.J., Calvino J.J., Marc M. - Lanthanide compound as environmentally friendly corrosion inhibitors of aluminium alloys: a review, *Corros. Sci.* **40** (1998) 1803-1819.
26. Liu X., Okafor P. C., Zheng Y. G. - The inhibition of CO₂ corrosion of N80 mild steel in single liquid phase and liquid/particle two-phase flow by aminoethyl imidazoline derivatives, *Corros. Sci.* **51** (2009) 744-751.
27. Forsyth M., Hinton B., Rare earth-based corrosion inhibitors, Woodhead Publishing, 2014.
28. Nam N. D., Motilal M., Bruce H., Mike J. Y. T., Forsyth M. - Rare earth 4-hydroxycinnamate compounds as carbon dioxide corrosion inhibitors for steel in sodium chloride solution, *J. Electrochem. Soc.* **161** (2014) C527-C534.
29. Sastri V. S. - Green corrosion inhibitors, John Wiley & Sons, Inc.Hoboken, New Jersey, 2011.