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Influence of Electrochemical Water Treatment on Carbon Steel Corrosion

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Chemicals known as corrosion inhibitors and their synergistic formulations have been employed for years in corrosion and scaling reduction processes in industrial cooling systems. Recent worldwide trends toward preserving natural resources, including the rationing of water resources, has led to the adoption of measures aimed at stimulating the reuse of water in industrial systems. Reusing water from other industrial units or effluent treatment stations as well as the reuse of rainwater are commonly used practices and have justified the development of new technologies for corrosion control. Of these technologies, the application of physical conditioners to control corrosion and scaling has been a primary goal for researchers because the use of these chemicals can reduce or eliminate the requirements for additional corrosion inhibitors in cooling water, lowering the costs associated with the subsequent treatment of the water. This work aimed to gather electrochemical data on synthetic cooling water under the effects of physical conditioning. The corrosion and deposition products were analysed using scanning electron microscopy (SEM) and X-ray diffraction (XRD). The results obtained in the tests with physical conditioners showed an increase in the dissolution process of metallic material due to a reduction in the precipitation of $CaCO_3$ on a metallic surface, which was caused by a greater exposure of the material to the action of the aggressive ions present in the synthetic cooling water.

Keywords: electrochemical water treatment, corrosion and scaling control, cooling systems, carbon steel

1. INTRODUCTION

Industrial cooling systems use large volumes of water and a variety of chemicals to control the corrosion of metallic components. However, the introduction of corrosion inhibitors into water leads to new requirements for further treatment to permit its reuse or disposal to the external environment.

These treatments can become onerous due to the great demand for water required in industrial cooling process.

The partial replacement and even definitively the chemical treatment of water by physical treatment in preventing and formation of deposits on metal surfaces of industrial equipment has been an alternative employed frequently in recent years. The main advantages to the physical treatment of water are reductions in environmentally undesirable products and low long-term costs. However, in terms of reducing the corrosive process, there are controversies of its action in relation to electrochemical mechanism. The main types of physical conditioners are:

- Magnetic Systems: these apply a magnetic field by means of magnets installed around the piping to stimulate the precipitation of $CaCO_3$ in water and decrease scaling in the cooling system;
- Electromagnetic Systems: these induce a magnetic and electric field in the cooling water flow, promoting the nucleation of salts present in water and reducing the severity of scaling on metallic surfaces;
- Electrostatic Systems: these modify the zeta potential of the cooling water, reducing the interaction particle forces and acting as an inhibitor to scaling and "bio-fouling";
- Electrochemical Systems: these favour homogeneous precipitation of $CaCO_3$ in the water flow by increasing the pH in the cathodic region caused by the electrochemical galvanic couple and the turbulent internal flow caused by conditioner;
- Electrolysis of water: this method involves the application of power from an external rectifier to increase the pH of the water at the surface of the electrode (cathodic), favouring the precipitation of $CaCO_3$ and its subsequent removal by a filtration process.

However, recent work [1] reports on the presence of scaling in industrial systems that use magnetic systems for physical treatment. Even so, a reduction in the potential for scaling through the formation of non-uniform deposits for easy removal has been observed [2] by modifying the nucleation and crystal growth processes of the $CaCO_3$.

A supersaturated salt solution may have either a homogeneous or a heterogeneous precipitation process. Homogeneous precipitation occurs within the fluid. The random collisions between ions cause the emergence of ionic clusters, which coalesce until they reach a critical core size. The cores act as origin sites for $CaCO_3$ crystals. Heterogeneous precipitation results from the presence of impurities, such as colloidal suspensions within the environment. These impurities act as the origin sites for the $CaCO_3$ crystals.

According to Busch *et al* [3], the result of the application of a magnetic field in a continuous flow is called a Magnetohydrodynamic force. For the force generated, the magnetic field must be oriented 90° to the direction of the flow. Any fluid with a high electrical conductivity that passes through the magnetic field lines experiences a Magnetohydrodynamic force. Under these conditions, the chance to obtain a homogeneous precipitation process increases. Alimi *et. al.* [4] reports that conditions favourable to homogeneous precipitation have been observed for a volumetric flow rate increase from 0.50 to 0.94 $L.min^{-1}$ in a medium containing 400 $mg.L^{-1}$ of $CaCO_3$ at a pH 6.0 and under the influence of a magnetic field. The formation of a significant amount of small $CaCO_3$ crystals was identified in the solution.

Li *et. al.* [5] affirms that the magnetic treatment of water promotes a conversion of calcite crystals (in the principal and most stable form) to aragonite (in orthorhombic or needle-shaped forms) and vaterite (with a hexagonal shape), which are less stable and porous and are easily removed from industrial systems. Kobe *et. al.* [6] observed this behaviour in a medium containing 300 $mg.L^{-1}$ of sodium bicarbonate and calcium at a flow velocity of 0.1 $m.s^{-1}$ (laminar regime). Through the use of a 1.3 T magnetic field, it is possible to determine that the precipitation of $CaCO_3$ occurs with a higher number of aragonite and vaterite crystals than calcite crystals through the use of X-ray diffraction (XRD) and transmission electronic microscopy (TEM). This reduces the deposit formation on the surface of the material. Gryta [7] also found that a variation in the flow of water containing 100 $mg.L^{-1}$ of $CaCO_3$ in a low intensity magnetic field (0.1 T) has an influence on the morphology of the precipitated $CaCO_3$. For laminar flow conditions (Re = 1400), it is possible to use scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) techniques to determine if there is preferential precipitation of calcite. However, for turbulent flow conditions, the amount of calcite precipitation is lower.

Previous research [2,6,8] has reported that an increase of ionic conductivity due to the presence of metallic ions in solution, such as Fe^{2+}, Zn^{2+} and Cu^{2+}, may change the morphology of the $CaCO_3$ crystals and reduce the amount of calcite crystals formed for an increase in the amount of aragonite crystals.

Therefore, the morphology of the $CaCO_3$ crystals depends on the magnetic flux density, the velocity of the fluid flow and the ionic conductivity of the solution. The formation of calcite particles is favoured under laminar flow conditions and for the application of a low intensity magnetic field ($<$ 0.4 T). Meanwhile, the formation of aragonite crystals is preferred under turbulent flow conditions and for the application of a higher intensity magnetic field ($>$ 0.5 T).

In this paper, we studied the effects of physical conditioning on corrosion and deposition processes on the surface of carbon steel. Among the previously mentioned physical conditioners, the electrochemical process was chosen for water treatment. This method is based on the union of two different metallic materials arranged in a configuration that induces a turbulent flow by constricting the fluid flow to increase the continuum velocity. A galvanic cell is formed upon the contact of water and the selected materials, which generate a galvanic potential that forms a cathodic region as a result of the water reduction process. In addition, the disposal of metals that are present in the conditioner is designed to induce turbulent flow conditions with the passage of water, which aims to increase the area of ionic contact with the water in the alkaline medium that is induced by the galvanic cell, leading to the formation of $CaCO_3$ in the water flow.

The tests were carried out using the physical conditioner in a loop, where electrochemical and gravimetric techniques were performed, to determine the corrosivity of the synthetic cooling water. To determine the potential for deposition, several physico-chemical parameters of the water – such as the amounts of the synthetic ions, Ca^{2+} ions, Cl^- ions and the pH – were monitored over time. At the end of the test, the products formed on the metallic surface were analysed to investigate the morphology and chemical composition of the resulting crystals.

2. METHODOLOGY

Laboratory tests were conducted using synthetic cooling water with 450 mg.L^{-1} of Ca^{2+} and 1050 mg.L^{-1} of Cl^-. The pH was adjusted to 7.5, and tests were performed at ambient temperatures. To monitor the corrosion processes, a closed circuit system (loop) was used to gather data, which was generated by polarisation curves, linear polarisation, electrochemical impedance, measurements of mass loss, scanning electron microscopy (SEM-EDS) and X-ray diffraction (XRD) during 35 days of immersion. The loop was composed of PVC pipes and connections with a 1 inch nominal diameter and total volume of 18 litres. The circulation of the cooling water in the loop was performed using a 1/125 hp centrifugal pump at a flow rate of 24 L.min^{-1}, resulting in a fluid velocity of 0.8 m.s^{-1}. The electrochemical conditioner was installed through a by-pass to allow it to be switched on and off depending on the desired test conditions.

Carbon steel coupons were used for the examination of the electrochemical techniques and to determine mass loss. A saturated calomel electrode (SCE) was used as a reference electrode. All measures were obtained using an electrochemical Pontentiostat AUTOLAB 302N. In addition, samples of the crystals formed on the surface of the coupons were collected and dried at 80ºC for scanning electron microscopy (SEM) and X-ray diffraction (XRD) analysis.

3. RESULTS AND DISCUSSION

3.1. Mass Loss

The gravimetric measurement tests were performed during the 35 day immersion period using the carbon steel coupons in accordance with ASTM G1-03 [9]. The purpose of these tests was to verify the effectiveness of the electrochemical treatment at controlling corrosion in the synthetic cooling water. The results obtained both with and without the application of the electrochemical treatment are described in Table 1:

Table 1. Corrosion rates for the carbon steel coupons from the mass loss test.

Test	Corrosion rate (mm/year)
No treatment	0.140
Treatment	0.337

The results of the corrosion tests are greater than the limit of 0.100 mm/year established by NACE RP-07-75 [10]. In the test using the electrochemical treatment, the corrosion rate is two times higher than the test performed without the treatment, indicating that the electrochemical treatment applied to the synthetic cooling water increased the corrosive process on the carbon steel surface. The lower corrosion rate obtained from the test without any electrochemical treatment may be related to the barrier of calcium carbonate ($CaCO_3$) that forms on the metallic surface. The diffusion of ions on the surface of the material is reduced by the presence of the $CaCO_3$ barrier, minimising the intensity of the metal dissolution process. Figure 1 illustrates the state of the coupon corrosion after the tests.

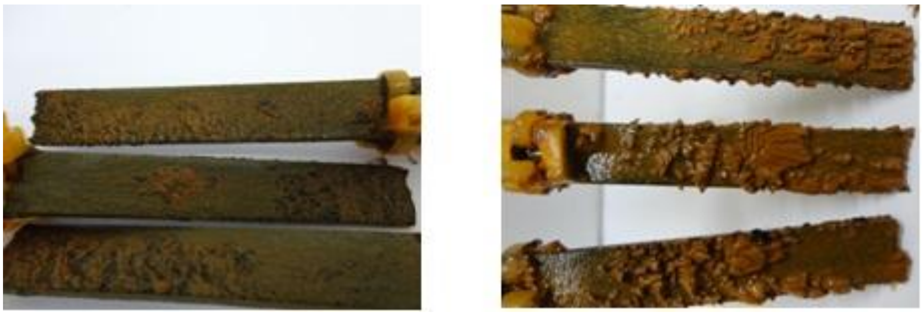

Figure 1. Corrosion products without the electrochemical treatment (left) and with the electrochemical treatment (right) in synthetic cooling water.

The greater amount of corrosion products on the coupons tested with the electrochemical treatment shows that the material deterioration process is more severe than for the coupons not exposed to the electrochemical treatment. The mechanism for uniform corrosion is present in both the tests.

3.2. Linear Polarisation and Electrochemical Impedance Spectroscopy:

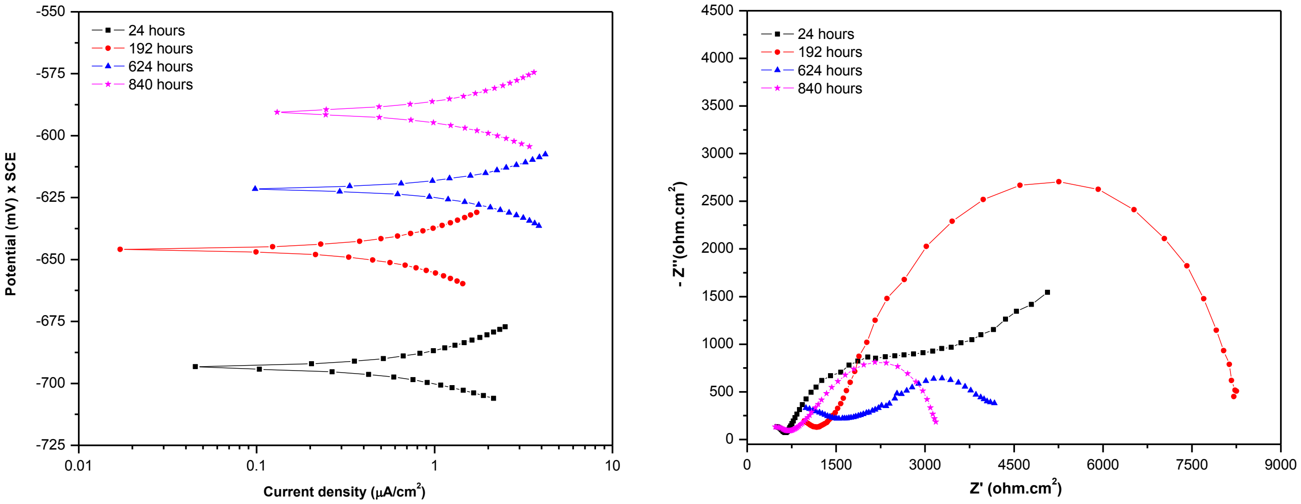

Figure 2. Linear polarisation (left) and electrochemical impedance (right) for the carbon steel coupons tested without the electrochemical treatment

Linear polarisation and electrochemical impedance techniques are used to determine the polarisation resistance (R_p) of the carbon steel coupons in relation to the synthetic cooling water for the two test conditions. Because these are non-destructive techniques, the acquisition of electrochemical data may be performed at different immersion times. For linear polarisation, the curves are obtained from the polarisation of the electrode over a range of ±15 mV in relation to the corrosion potential. Using the potential and current density results, it is possible to use linear regression to determine the polarisation resistance. Nyquist plots are obtained through the application of a scanning frequency within the range of 10000 to 0.01 Hz to determine electrochemical impedance. The polarisation resistance is determined through the extrapolation of the graphical capacitive arcs. Figure 2 shows the linear polarisation and electrochemical impedance obtained with and without the use of an electrochemical treatment.

Table 2 lists the linear polarisation and electrochemical impedance values for different polarisation resistances.

Table 2. Polarisation resistance of the carbon steel coupons tested in the synthetic cooling water without the electrochemical treatment

Electrochemical technique	Polarisation resistance (KΩ. cm^2)			
	24 hours	192 hours	624 hours	840 hours
Linear polarisation	6.23	8.65	4.31	3.34
Electrochemical impedance	6.16	7.42	4.74	2.94

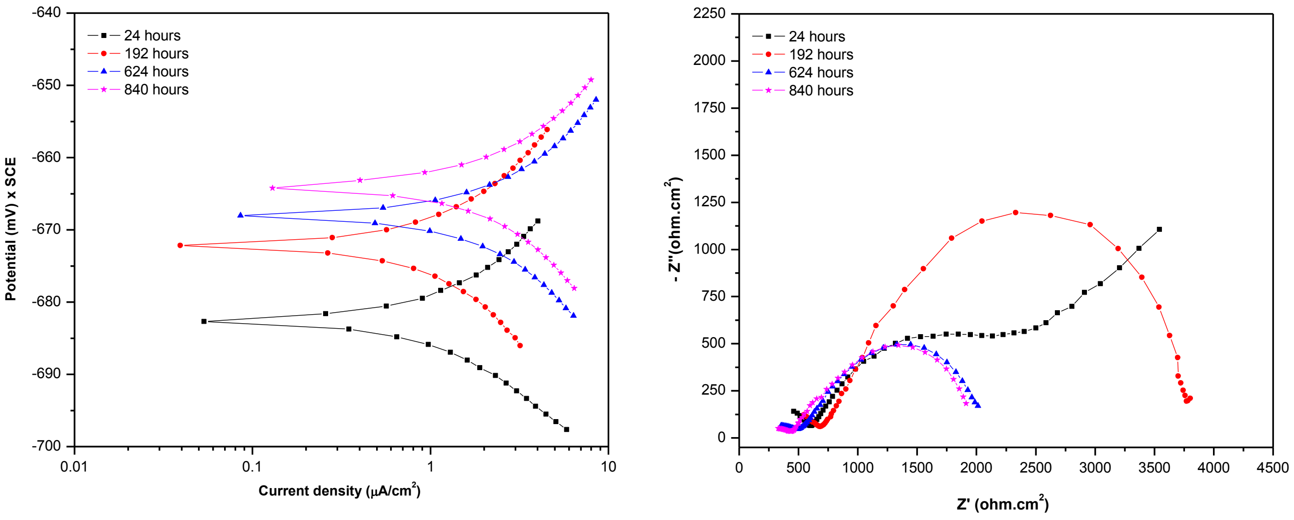

Figure 3. Linear polarisation (left) and the electrochemical impedance (right) for the carbon steel coupons tested with the electrochemical treatment

According with both electrochemical techniques, the corrosive process may be minimised for an immersion time of up to 192 hours. This is confirmed by the higher linear polarisation resistance and the lower current density. These results are coherent with the electrochemical impedance data presenting a higher capacitive arc. Thus, the polarisation resistances obtained from the two electrochemical techniques are higher for this immersion period. The formation of a protective layer of calcium carbonate on the surface of the material due to the hardness of the synthetic cooling water used in the tests may have contributed to the reduction of the corrosion rate. Similarly, the high salinity levels present in the solution, characterised by the presence of chloride ions, may have been responsible for ion diffusion through the calcium carbonate barrier, accelerating the corrosion process during the 192 hour immersion period, which was characterised by a reduction in the polarisation resistance of the carbon steel. In the test using the electrochemical treatment, the uniform corrosion process is more pronounced, as illustrated in Figure 3.

An analysis of the data in Figure 3 shows that it is possible to verify that the corrosion rate decreases over the 192 hour immersion period. However, the deterioration of the material was more intense when the electrochemical treatment was used, with higher values of current densities in linear polarization and smaller capacitive arcs in electrochemical impedance compared to the test without the electrochemical treatment. Table 3 shows the data obtained from the polarisation resistance of the carbon steel for the two electrochemical techniques used in this test.

Table 3. Polarisation resistance of the carbon steel coupons tested in the synthetic cooling water with the electrochemical treatment

Electrochemical technique	Polarisation resistance (KΩ. cm^2)			
	24 hours	192 hours	624 hours	840 hours
Linear polarisation	2.94	3.23	2.09	1.93
Electrochemical impedance	2.41	2.62	1.75	1.68

The polarisation resistance is lower with the application of the electrochemical treatment than without the electrochemical treatment. The reason for this difference may be associated with the action of the electrochemical treatment for the homogeneous conditions that were observed for the precipitation of $CaCO_3$. The formation of calcium carbonate crystals in the water flow through the collision of ionic species present in the solution as a result of the electrochemical treatment may cause a greater exposure of the metal surface to corrosive attack, leading to an increase in the amount of metal dissolution.

Ge *et. al.* [11] observed the influence of electromagnetic fields on the corrosion rate of carbon steel in a solution containing 60 mg.L^{-1} of Ca^{2+}, 366 mg.L^{-1} of HCO_3^-, 48 mg.L^{-1} of SO_4^{2-}, 106,5 mg.L^{-1} of Cl^- and 12 mg.L^{-1} of Mg^{2+} at room temperature. Electrochemical impedance and polarisation curves techniques respectively showed that the polarization resistance decreased and corrosion current density increased when the electromagnetic treatment was used. These results confirm that such treatment also increased the corrosion rate of carbon steel in synthetic cooling water.

Figure 1 illustrates the amount of corrosion on the surface of the carbon steel coupons for both tests, showing that the polarisation resistance values agree with the results from the gravimetric test and can be used as an electrochemical parameter in the assessment of the corrosivity of the water.

3.3. Polarisation Curves:

The cathodic and anodic polarisation curves for the carbon steel coupons in the synthetic cooling water were obtained with and without the electrochemical treatment. The scanning rate for the test was 0.33 mV.s^{-1} and was performed over a range of 600 mV in relation to the corrosion potential. The curves were obtained at different immersion times to verify the evolution of the corrosion process. Figures 4 and 5 show the polarisation curves for the tests.

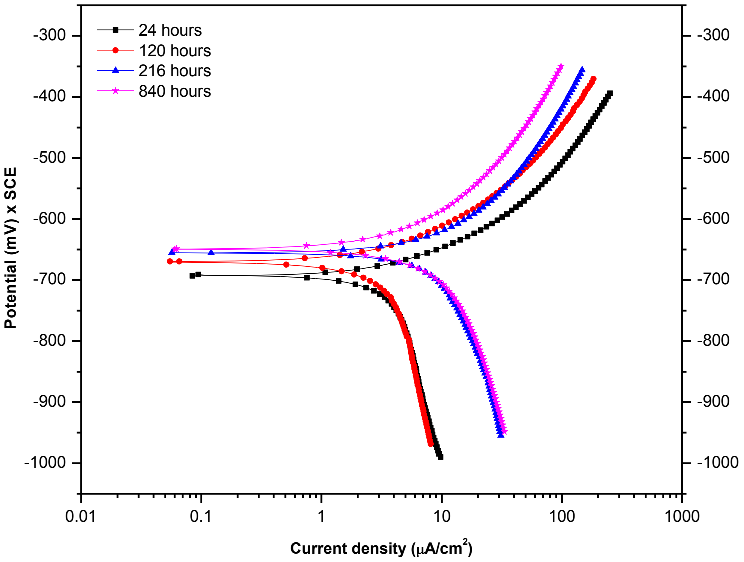

Figure 4. Cathodic and anodic polarisation curves for the carbon steel coupons in the synthetic cooling water at a pH 7.5 and an ambient temperature without the electrochemical treatment.

Figure 4 shows that active dissolution is present throughout the entire test, as shown with the increase in the current density. However, it is important to note that until the end of the 192 hour immersion period, there was a reduction of the cathodic current density to approximately 10 μA.cm^{-2}. The formation of an adherent and uniform barrier of $CaCO_3$, likely in the form of calcite particles on the surface of the carbon steel, may minimise the spread of oxygen on the surface as well as inhibit the corrosive process. However, after the 192 hour immersion period, the dissolved oxygen in the water passed through the $CaCO_3$ barrier, and the dissolution processes continued to deteriorate the material, as characterised by the evolution of the current density. When the electrochemical treatment was used to control the corrosion of the carbon steel coupons in the solution, the resulting polarisation curves almost coincided, as shown in Figure 5. The highest current densities and the small variations in the corrosion potential at all the evaluated immersion times indicate an accelerating metallic deterioration process. Zubiate *et al.* [12] observed the influence of magnetic fields on the corrosion rate of carbon steel. The material was exposed to a water flow rate of 0.77 m.s^{-1} and a magnetic field (1 T). After 200 hours of immersion, the polarization curves showed that the corrosion rate increased with the application of the magnetic treatment, where the anodically polarized material indicated an active dissolution process, and the cathodically polarized material exhibited an increase in current density.

In accordance with the previous electrochemical tests, the results demonstrate that the use of the electrochemical treatment in the loop probably increases the corrosion rate of the carbon steel coupons due to the homogeneous precipitation induced by the electrochemical treatment. This encourages the formation of $CaCO_3$ in the water flow, increasing the exposure of the carbon steel surface in the solution with high salinity. Therefore, the use of the electrochemical treatment proved to be inefficient for the case reported here.

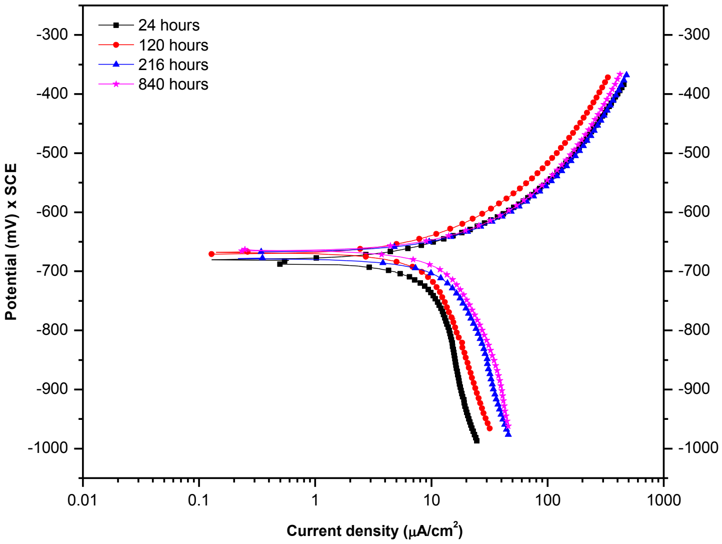

Figure 5. Cathodic and anodic polarisation curves for the carbon steel coupons in the synthetic cooling water at a pH 7.5 and an ambient temperature using the electrochemical treatment.

3.4. X-Ray Diffraction Technique:

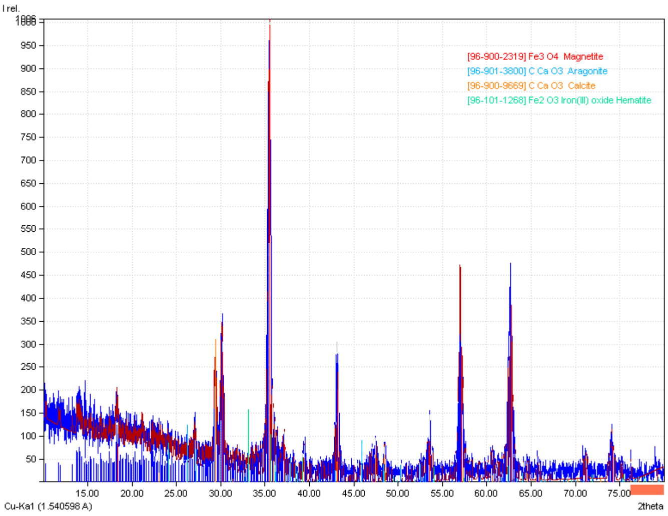

Figure 6. Powder diffractogram of the crystals on the surface of the carbon steel corrosion coupon generated without the electrochemical treatment in the synthetic cooling water.

To evaluate the structure of chemical species present on corrosion coupons, the crystals deposited on the surface were analysed using X-Ray Diffraction with Cu-Kα radiation. The data were recorded using the Match program (version 2.0.9) to determine the structure of the crystal. Figure 6 shows the powder diffractogram obtained from the test that did not use the electrochemical treatment. It is possible to obtain the structure and quantity of the products formed on the surface of the corrosion coupons, as shown in Table 4.

Table 4. Quantity of crystals formed on the surface of the carbon steel corrosion coupons without the electrochemical treatment.

Product	Formula	Quantity (%)
Magnetite	Fe_3O_4	42.4
Aragonite	$CaCO_3$	26.6
Calcite	$CaCO_3$	22.2
Hematite	Fe_2O_3	8.8

From Table 4, the conditions that arise from the absence of the electrochemical treatment in the synthetic cooling water induce the formation of a layer of calcium carbonate on the metallic surface of carbon steel. The calcium carbonate adheres to the surface and leads to the formation of magnetite under the precipitate on the carbon steel coupon. Magnetite is a compact and adherent oxide that forms in small aerated regions and acts as a protective barrier. Thus, the adhesive mechanical barrier that forms on the surface of the carbon steel is composed mainly of calcium carbonate and magnetite.

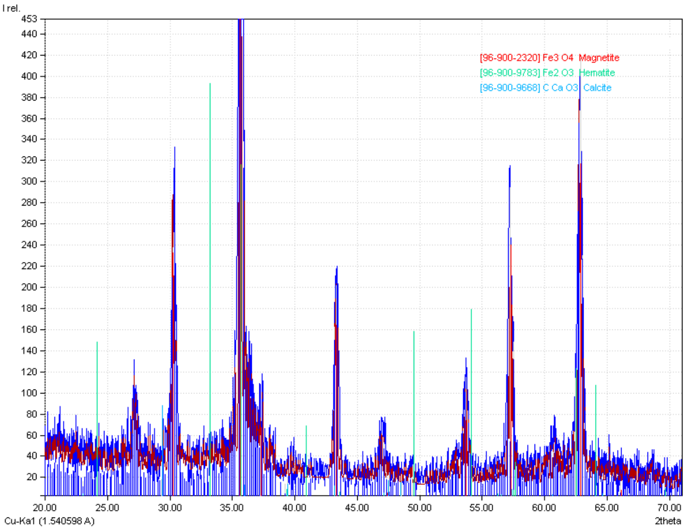

Figure 7. Powder diffractogram of the crystals formed on the surface of the carbon steel corrosion coupon tested with the electrochemical treatment in the synthetic cooling water.

Aragonite constitutes a greater proportion of the $CaCO_3$ protective barrier than the calcite. As previously described, the high conductivity of the solution [2,6,8] and the turbulent flow conditions [7] in the test may promote the formation of the aragonite form of calcium carbonate. However, because aragonite is an unstable and porous product, ion permeation on the metallic surface is facilitated by an increase in the immersion time. Similarly, hematite forms in aerated regions and provides little protection due to its being porous and easily removed. Therefore, the hardness of the synthetic cooling water is responsible for the formation of a non-uniform $CaCO_3$ uniform barrier on the metallic surface. The greater percentage of iron oxides shows that the high salinity in the solution permeates the $CaCO_3$ layer, accelerating the corrosion process.

In the test using the electrochemical treatment, the deposit that formed on the metallic surface of the carbon steel coupon showed more intense and numerous peaks, as illustrated in Figure 7.

Table 5 shows the characterised products that formed on the carbon steel corrosion coupons according to the powder diffractogram analysis shown in Figure 7:

Table 5. Quantity of crystals formed on the carbon steel corrosion coupons tested with the electrochemical treatment.

Product	Formula	Quantity (%)
Magnetite	Fe_3O_4	50.4
Hematite	Fe_2O_3	40.8
Calcite	$CaCO_3$	8.8

The X-Ray diffraction technique showed that using the electrochemical treatment in the synthetic cooling water modified the structure of the calcium carbonate crystal. The aragonite crystalline form was not detected in the product formed on the metallic surface after the test, which was likely a result of the homogeneous precipitation process that was induced by the electrochemical treatment. The aragonite that formed as part of the calcium carbonate precipitation should have remained in the water flow due to the localised increase in the pH of the water, which was a result of the electrochemical treatment, reducing the precipitation on the metallic surface. Another aspect was the reduction of the calcite form of calcium carbonate in the solution. A possible conversion of the calcite form of $CaCO_3$ to the aragonite form might have been caused by the homogeneous precipitation process. The turbulent flow conditions add to the increase in localised pH that may lead to an increase in the number of ionic collisions and the formation of small clusters of $CaCO_3$ at the centre of the water flow. The resulting cores coalesced until reaching a critical size and grew to modify the structure of the crystal. However, the amount of magnetite and hematite was greater than the amount calcium carbonate, indicating an increase in the corrosive process on the metallic surface. Therefore, the results of the diffraction analysis for the two test conditions agree with the electrochemical techniques described previously, for which the use of the electrochemical treatment favours the homogeneous precipitation process for $CaCO_3$ and the degradation of the carbon steel.

3.5. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS):

Several analyses were performed using scanning electron microscopy to determine the morphology of the calcium carbonate crystals. Figures 8 and 9 shows the micrographs and the EDS spectra obtained for each test.

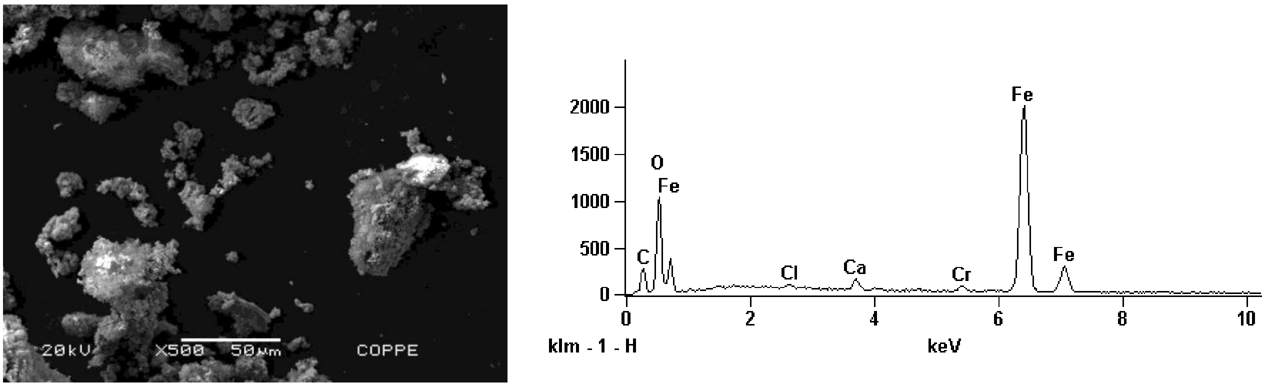

Figure 8. SEM micrographs and EDS spectra for the products formed on the carbon steel corrosion coupons tested without the electrochemical treatment in the synthetic cooling water.

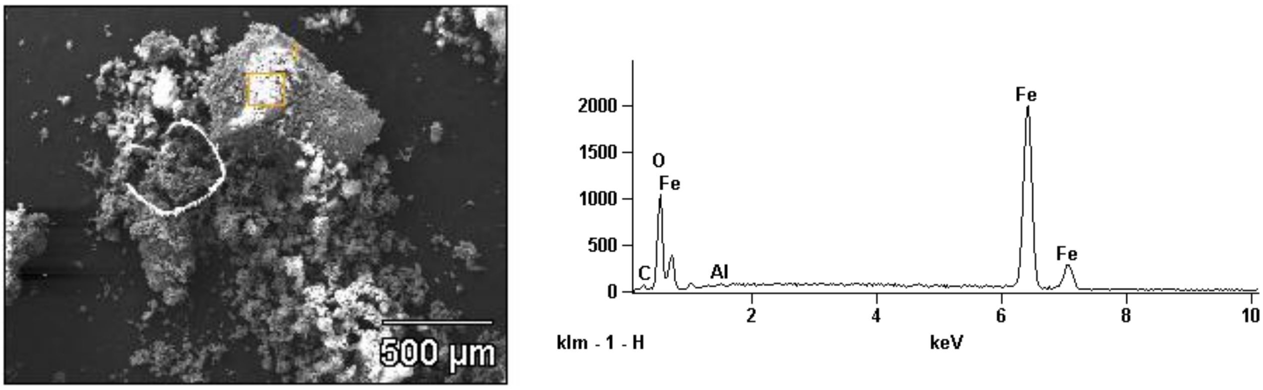

Figure 9. SEM micrographs and EDS spectra for the products formed on the carbon steel corrosion coupons tested with the electrochemical treatment in the synthetic cooling water.

Without the electrochemical treatment, the shape of the crystals identified with SEM were consistent with hematite and magnetite and were characterised a by hexagonal shape. Despite the EDS spectra, which showed a small calcium (Ca^{2+}) peak, the presence of calcite crystals (romboedrical form) was not distinguishable in a micrograph. It is theorised that better positioning and greater SEM approximation may be able distinguish the presence of calcite crystals. However, the micrographs show the formation of defined and compact crystals, which were likely caused by the formation of calcite in the oxide barrier on the surface of the metal. When the electrochemical treatment was employed, the crystals that formed also exhibited hexagonal structures, as observed in the micrographs shown in Figure 9. The EDS spectra indicate the presence of elements that are consistent with hematite and magnetite oxides, showing that the homogeneous precipitation process caused by the electrochemical treatment reduces calcium carbonate formation on the carbon steel surface, increasing the corrosive process.

The possibility of using alternative technologies to control corrosion in industrial waters remains as a permanent and controversial issue. Many authors support this idea and claim that the use of chemical compounds, such as corrosion inhibitors, can be avoided by using different physico-chemical methods, among them the electrochemical process here described. On the other hand, many researchers are quite skeptical and claim that those treatments have no influence on the water characteristics. From the results here presented and discussed it was possible to detect the effect of an electrochemical device on the composition and structure of deposits formed on carbon steel/water interfaces. Additionally, the impact of these deposits on corrosion was demonstrated by using electrochemical measurements and mass loss tests. The major conclusion is that although the electrochemical method exhibits a potential reduction of the amount of deposit formed, and consequently slowing down incrustation, the corrosion rate is increased. These conclusions could not be achieved without the support of the results obtained in the present research. The link among the characteristics of the deposit formed with and without the influence of the electrochemical device and corrosion process can considered as the major and novel contribution of this work.

4. CONCLUSIONS

- The mass loss test yielded corrosion rates greater than 0.100 mm/year for the uniform corrosion mechanism at both conditions evaluated. The exposure of the material to corrosion attack was greater when tested with the electrochemical treatment, possibly due to the greater dispersion of the calcium carbonate in the aqueous media and due to the limited access to the metallic surface.
- The linear polarisation and electrochemical impedance techniques showed that using the electrochemical treatment in the synthetic cooling water increased the homogeneous $CaCO_3$ precipitation process in the water flow, causing the exposure of the material to corrosive attack. This was due to the polarisation resistance being less than that for the test without the treatment.
- The cathodic and anodic polarisation curves obtained for the two test conditions showed an active dissolution process in the carbon steel. Without the catalytic treatment, the intensity of the corrosion process was less than if the electrochemical treatment was used for up to a 192 hour immersion period due to the reduction of cathodic current density, which was possibly a result of the presence of a $CaCO_3$ barrier that adhered to the metallic surface.
- The X-ray diffraction technique showed that the electrochemical treatment promoted the exposure of the material to corrosive attack due to an increase in the homogeneous $CaCO_3$ precipitation process in the water flow. However, the presence of aragonite and calcite on the surface

of the coupon tested without the electrochemical treatment showed a small reduction in corrosion on the surface of the coupon, which resulted from the formation of a $CaCO_3$, magnetite and hematite barrier.

- The scanning electron microscopy technique showed that the predominant morphology in both tests was hexagonal hematite and magnetite crystals, which was confirmed by X-ray diffraction. In the test using the electrochemical treatment, the absence of calcium crystals in EDS spectra led to the observation that the calcium carbonate remained dispersed in the water, favouring the deterioration process of the material by the corrosive action of water.
- It was possible to detect the effect of an electrochemical device on the composition and structure of deposits formed on carbon steel/water interfaces. Additionally, the impact of these deposits on corrosion was demonstrated by using electrochemical measurements and mass loss tests.
- Although the electrochemical method exhibits a potential reduction of the amount of deposit formed, and consequently slowing down incrustation, the corrosion rate of carbon steel in synthetic cooling water is increased.

References

1. K. W. Busch, M. A. Busch, *Desalination*, 109 (1997) 131 - 148;
2. L. C. Lipus, D. Dobersek, *Chemical Engineering Science*, 62 (2007) 2089- 2095;
3. K. W. Busch, M. A. Busch, D. H. Parker, R. E. Darling, J. L. Mcatee, *Corrosion*, 42 (1986) 211-221;
4. F. Alimi, M. Tlili, M. B. Love, C. Gabrielli, G. Maurin, *Desalination*, 206 (2007) 163 - 168;
5. J. Li, J. Liu, T. Yang, C. Xiao, *Water Research*, 41 (2007) 4595 - 4610;
6. S. Kobe, G. Drazic, P. J. McGuiness, J. Strazisar, *Journal of Magnetism and Magnetic Materials*, 236 (2001) 71 - 76;
7. M. Gryta, *Separation and Purification Technology*, 80 (2011) 293 - 299;
8. C. Gabrielli, R. Jaouhari, G. Maurin, M. Keddam, *Water Research*, 35 (2001) 3249-3529;
9. ASTM G1-03, 2003: Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test 'Specimens;
10. NACE RP-07-75, 2005: Preparation, Installation, Analysis, and Interpretation of Corrosion Coupons in Oilfield Operations;
11. H. H. Ge, J. T. Tao, X. M. Gong, C. J. Wei, X. M. Xu, *Advanced Materials Research*, 347 (2012) 3135-3138;
12. E. M. B. Zubiate, A. M. V. Alvarez, F. A. Calderón, J. A. M. Aquino, *J. Alloys and Compounds*, 369 (2004) 256-259;