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NUMERICAL STUDY AND REMEDIATION OF AC INTERFERENCE CORROSION ON NEIGHBOURING PIPELINES

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Abstract

Buried pipelines for gas and oil are protected by an insulation coating and a Cathodic Protection (CP). However, neighbouring high voltage HV power lines induce an alternating current AC which causes corrosion damages on metallic structures, even in CP conditions, this phenomenon is known as the AC corrosion. In our study, we conducted a substantial theoretical research in this field to explain the basic electrical and electrochemical mechanisms of corrosion by AC. Afterwards; we performed numerical simulation studies of the electrochemical reactions involved in the corrosion, such as the anodic and cathodic processes, i.e., the iron oxidation and reduction of both oxygen and hydrogen. We also simulated the CP, AC corrosion, and deformation of the steel pipeline sample. Finally, in order to remedy this problem, we developed a monitoring and correction program for optimising the AC corrosion. In this article, we presented the study of the chemical behaviour of iron, oxygen and hydrogen. Moreover, we applied the rectification program, which did never exist in previous studies.

Keywords: AC corrosion, Cathodic protection, Electrochemical tests, Immunity zone, Reference potential.

1. Introduction

According to the ISO 8044-2000, corrosion is defined as a "physicochemical interaction between a metal and its environment resulting in changes in the properties of the metal and may lead to a significant deterioration in the function of the metal, the surrounding environment or their technical system" [1]. Buried pipelines are influenced by AC currents induced by high voltage overhead by both of an insulation coating and a Cathodic Protection (CP) and then serious damage by corrosion will take place.

More recently, some examples of corrosion caused by alternating current AC (50 Hz) on gas canalization were found [2]. The corrosion by AC of buried metallic structures has become a problem only in the last thirty years, following the growth in the number of so-called interference sources, for example, the traction systems and electrical transmission lines AC-powered, and of the structures buried pipes, for the transport of gases or oil, that share the path with the above-mentioned sources for long distances because of the space limitation imposed by private or governmental entities [3, 4]. In recent decades, the improvement of the insulation capacity of the cathodically-protected pipe coatings has aggravated the problem of corrosion by AC: the passage to the use of the bitumen and particularly polyethylene and polypropylene extruded, allowed to increase the electrical resistivity of the coatings and to minimise the size and the number of defects. This is an advantage because it reduces the current CP to be delivered but causes at the defects area high densities of interfering AC. This is considered by many authors as one of the main reasons for the growth in the number of cases of corrosion attributable to the interference by AC [4-9] And a substantial studies have been carried out in this field, by many researchers as Brenna et al [3], Nielsen et al. [6], Christoforidis et al. [9], Gupta et al [10], Ding and Fan [11], Ibrahim et al [12], Yan et al [13] and NACE International [14].

In gas and oil companies, a serious AC corrosion problem of buried pipelines has been confronted, even in a protection condition by both of an insulation coating and a Cathodic Protection (CP). To remedy the problem, the companies are opting to replace defective sections, which is economically very costly.

To resolve this problem, our research goals are to simulate this phenomenon and conducting investigations which are summed up in three points; first, we conducted a theoretical research to explain the basic electrical and electrochemical mechanisms of corrosion by the alternating current, the second point is carrying out an electrochemical tests on a laboratory model by using a sample of pipeline steel type API 5L X52, which is used in Algeria; for realizing our experimental investigation, we used an advanced electrochemical workstation potentiostat and galvanostat EC-LAB VSP300. It allowed us to simplify the model of the studied phenomenon, and it provided all of our measurements, we used a test cell containing a pipeline's sample, and a solution to simulate the electrolyte.

The test cell was first subjected to measurements of the free potential, which means without the both of CP and AC and secondly, we applied to the sample a DC as CP, the measurements of the reference potential E_{off} close to the iron sample allowed us to select an appropriate CP, then we added an AC current in order to simulate the induced current. The results have shown that the induced AC current causes the corrosion of the sample even in Cathodic Protection condition [15, 16]. The third point, we did simultaneously with the second one, is a numerical simulation

study in order to digitally represent the test cell, the CP phenomenon and the AC corrosion, we also suggested an efficient solution for minimising its impact on pipelines. This numerical simulation of the process was possible by using the COMSOL Multiphysics software [17-20], we introduced all parameters of both of the iron sample and the electrolyte simulating. We measured the E_{off}, we selected the appropriate CP, which brings the immunity state, and then we added AC for simulating induced current. In this last case, the measured results gave an E_{off} exceeding the immunity zone regarding standards [8, 21, 22], a strong oxidation of iron, a significant reduction of oxygen, a high liberation of hydrogen and a clear sample deformation.

All these results mean that our sample of the pipeline, which was protected by CP, when it was subjected to an induced AC its corrosion, took place. These numerical results validate the experimental study results. Finally, we have set up a monitoring and correction program to bring the E_{off}, in the presence of AC, in the immunity corrosion zone according to standards; our monitoring program was able to minimize the reactions of the electrochemical process and it prevented the sample's deformation, because it can testing, calculating and choosing automatically in each case a safety CP. This article is dedicated to the explanation of the study of the numerical simulation part.

2. Theoretical Study of Corrosion by AC

We conducted a conscientious theoretical research, it showed us the main AC corrosion mechanism of pipelines API type, it illustrated to us multiple points such as the different types of AC interference [3], the corrosion by AC [3, 22], the explanation of electrochemical corrosion, [23], the standards, the pourbaix diagram (as shown in Fig. 1) of corrosion and immunity areas [3, 4, 21], the Cathodic Protection [3, 23], the measurement parameters of corrosion [3] and the principal models of the corrosion mechanism by AC [24].

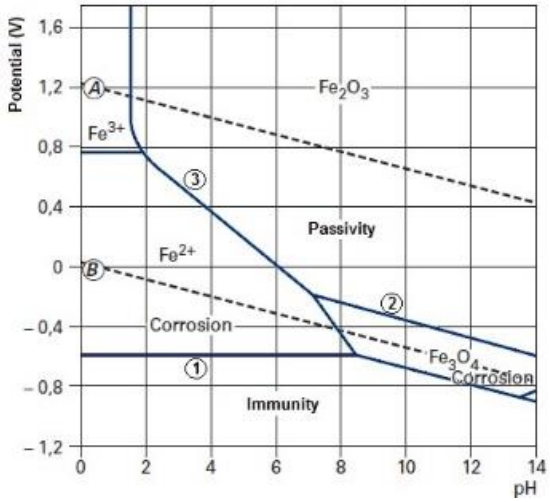


Fig. 1. Iron pourbaix diagram of corrosion and immunity areas [3, 21].

Below the reactions of the electrochemical process [2, 3, 23, 24]:

Anodic process:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (1)$$

Cathodic process:

$$4e^{-} + O_2 + 2H_2O \rightarrow 4OH^{-} \quad (2)$$

$$2e^{-} + 2H_2O \rightarrow 2OH^{-} + H_2 \quad (3)$$

$$2e^{-} + 2H^{+} \rightarrow H_2 \quad (4)$$

The topics studied in the theoretical part are:

- AC interferences.
- Electrochemical corrosion of steel.
- Pourbaix diagrams.
- Cathodic protection.
- Thermodynamic effect.
- Kinetic effect.
- Chemical effect.
- Cathodic Protection monitoring.
- AC corrosion, characteristics.
- AC Cathodic Protection criteria.
- AC corrosion monitoring.
- AC interference mitigation.
- Models of the AC corrosion mechanism, such as model extracted from technical specification CEN / TS 15280, equivalent electrical circuit model, electrochemical model, mathematical models and AC tidal effect model.

3. Numerical Modelling

We did a simulation study in order to, digitally represent the CP phenomenon, AC corrosion and optimizing AC corrosion behaviour by changing the CP in case of AC interferences, by a monitoring program, which returns process status to the immunity zone, by referring to pourbaix diagram and CP criteria suggested by Hosokawa [3, 8, 21, 22]. The immunity zone is -1.15 V < E_{off} < -0.85 V, where E_{off} is the reference potential sensed by the reference electrode. Numerical simulations are based on:

3.1. The model geometry

The model geometry used in the simulation part contains the sample, the electrode and the electrolyte as shown in Fig. 2.

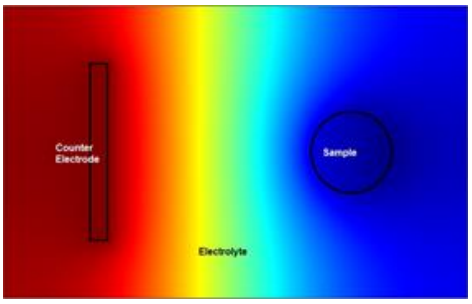


Fig. 2. The model geometry (sample, counter electrode and electrolyte).

This simulation requires:

The configuration of parameters initial value [17-20]: Electrolyte conductivity; Diffusion coefficient of *Fe* (iron), O_2 (oxygen) and H_2 (hydrogen), Tafel slope iron oxidation, hydrogen evolution and oxygen reduction, Reference concentration of *Fe*, O_2 and H_2, iron oxidation equilibrium potential, hydrogen evolution equilibrium potential, oxygen reduction equilibrium potential, iron oxidation exchange current density, hydrogen evolution current density and oxygen reduction exchange current density.

The definition and the electrochemical composition of iron API 5L X52 pipeline used in Algeria (sample in Fig. 2) in the "Material Overview" COMSOL section [17-20]: Thermal conductivity (W/(m.K)), Resistivity (Ω.m), Surface emissivity, Coefficient of thermal expansion (1/K), Heat capacity at constant pressure (J/(kg.K)), HC (J/(mol.K)), Electrical conductivity (S/m), Density (kg/m^3), VP (Pa), Tangent coefficient of thermal expansion (1/K), Thermal strain, Isotropic tangent coefficient of thermal expansion (1/K), Isotropic thermal strain, Young's modulus (Pa), Poisson's ration, Bulk modulus (N/m^3) and Shear modulus (N/m^3).

The definition of the reference electrode is in the "Domain Probe– Definition" COMSOL section [17-20]: The Probe, Probe type, Source application (Sample surface), Calculation type (average).

The definition of the electrolyte used ($NaCl + Na_2SO_4$) is in the "Material" COMSOL section [17-20]: Thermal conductivity (W/(m.K), Heat capacity at constant pressure (J/(kg.K), HC (J/(mol.K) and VP (Pa).

3.2. The parameterization of current distribution in the cell

The electrode is a metallic conductor, thus its current-voltage relation is obeyed to ohm's law [21, 25, 26]:

$$i_s = -\sigma_s \nabla \Phi_s \qquad \text{with} \qquad \nabla . i_s = Q_s \tag{5}$$

where i_s is the current density (A/m^2) in the electrode, σ_s is the conductivity (S/m), Φ_s is the electric potential (*V*), and Q_s is the general current source term (A/m^3).

The electric potential Φ_s is defined as [3, 27]:

$$\Phi_s = E_{CP} + E_{AC} = E_{CP} + A.\sin(2\pi.f.t) \quad (6)$$

where E_{CP} is the applied potential of CP, E_{AC} is the AC potential, A is the amplitude of the AC potential and f is the frequency (50 Hz).

The electrolyte, which is an ionic conductor, the net current density can be described, using the sum of fluxes of all ions [21, 26]:

$$i_l = F\sum_i z_i.N_i \quad (7)$$

where i_l is the current density (A/m^2) in the electrolyte, F is Faraday constant (C/mol), and N_i is the flux of species i (mol.(m^2/s)) with charge number z_i.

The flux of an ion in an ideal electrolyte solution is described by the nernst-planck equation and accounts for the flux of solute species by diffusion, migration, and convection in the three respective additive terms [21, 26]:

$$N_i = -D_i\nabla c_i - z_i u_{m,i} F c_i \nabla\Phi_l + c_i u \quad (8)$$

where for the specie i, c_i is the concentration (mol/m^3), D_i is the diffusion coefficient (m^2/s), $u_{m,i}$ is its mobility (s·mol/kg), Φ_l is the electrolyte potential (V), and u is the velocity vector (m/s).

On substituting the nernst-planck equation into the expression for current density, we find [21, 26]:

$$i_l = -F\left(\nabla\sum_i z_i D_i c_i\right) - F^2\nabla\Phi_l \sum_i z_i^2 u_{m,i} c_i + uF\sum_i z_i c_i \quad (9)$$

with conservation of current: $\nabla.i_l = Q_l$

This general treatment of electrochemical theory is usually too complicated to be practical. By assuming that one or more of the terms in Eq. (9) are small, the equations can be simplified and linearized [21, 25, 26, 28, 29]:

$$i_l = -\sigma_l\nabla\Phi_l \text{ with } \nabla.i_l = Q_l \quad (10)$$

The difference between the actual potential difference and the equilibrium potential difference is the activation overpotential η (electrode-electrolyte-interface) [21, 26, 28, 29, 30]:

$$\eta = Q_s - Q_l - E_{eq} \quad (11)$$

where E_{eq} is the equilibrium potential and it is given by nernst's equation [3]:

$$E_{eq} = E_0 + K.\log\left(\frac{a_{M^{z+}}}{a_M}\right) \quad (12)$$

3.3. The transport of chemical species

In order to configure the concentration and the chemical species movement (Fe, O_2, H_2) [31], the driving forces for transport can be diffused by Fick´s law, convection when coupled to a flow field, and migration, when coupled to an electric field [26].

$$(\sigma c_i / \sigma t) + \nabla(-D_i \nabla c_i) + u.\nabla c_i = R_i \quad (13)$$

where for the specie i, c_i is the concentration (mol/m^3), D_i is the diffusion coefficient (m^2/s), u is the velocity vector (m/s), and R_i is the reaction rate expression (mol/(m^3.s)).

The flux vector N is associated with the mass balance equation above and used in boundary conditions and flux computations. For the case where the diffusion and convection are the only transport mechanisms, the flux vector is defined as [26]:

$$N_i = -D_i \nabla c_i + u c_i \quad (14)$$

3.4. The math ODE and DAO

We used this module in COMSOL multi-physics to support the monitoring program Fig. 3 in order to bring the situation to the immunity state, below the simplified algorithm used:

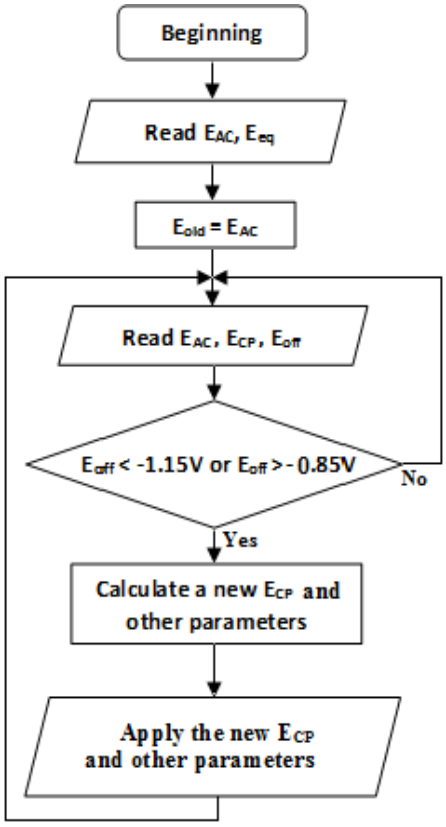


Fig. 3. Simplified program to return in the immunity zone.

The basic idea of the immunity program resides in its function as a monitor controller, it loops indefinitely so that the system (the sample, CP and E_{off}) stays continually under monitoring.

As long as there is no overrun of E_{off} of the immunity zone limits (-1.15V <E_{off} <-0.85 V) the program loops without doing anything. But, in case of overcoming, the program rectifies the CP, taking into consideration the previous value of CP and the sensed values of E_{off} and AC, until the E_{off} returns to the immunity area.

3.5. The deformation of the sample by corrosion

We applied the corrosion-secondary model wizard of COMSOL to our model [17-20]. It is a predefined multiphysics interface that contains an interface for the electric current distribution and an interface for deformed geometry. The last handle the deformed geometry part of the problem.

For the counter electrode surface, which was not deformed, we used an electrode surface node to model the reduction reaction. For the sample surface, we used an electrode surface node with an added dissolving-depositing species, which set up both the deformation of the geometry and the steel electrode reactions.

We also solved the model using a time-dependent study with automatic remeshing enabled [17-20].

Based on the cathodic tafel expression to describe the kinetics of the reaction and anodic Tafel expression for the anodic electrode reaction current density [28, 30, 32-35]:

$$i_{cat} = -i_{0,cat}.10^{\frac{\eta}{A_{cat}}}, \qquad i_{tafel} = -i_{0,an}.10^{\frac{\eta}{A_{an}}} \tag{15}$$

$$i_{an} = \frac{\left(i_{tafel}.i_{\lim}\right)}{\left(i_{tafel} + i_{\lim}\right)} \tag{16}$$

where i_0 is the exchange current density, η is the overpotential of the reaction and A_{an} A_{cat} are the Tafel slope, and i_{lim} is limiting current density.

The dissolution of iron metal makes the electrode boundary moving, with a velocity in the normal direction, v (m/s), according to:

$$v = \left(\frac{i_{an}}{2F}\right).\left(\frac{M}{\rho}\right) \tag{17}$$

where M is the average molar mass, ρ is the density of the iron, F is the Faraday const. (C/mol).

4. Results and Discussion

4.1. The potential E_{off} in the presence of CP

Figures 4 to 9 represent the E_{off} in the presence of CP and for different values of an induced current AC, without than with the immunity program, this representation allowed us to discuss, following the curves of the corrosion of the sample, based on the standards [1, 3, 8, 21, 22].

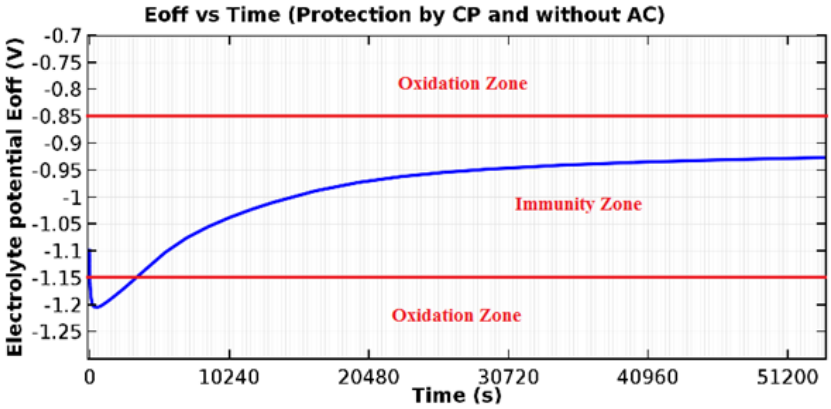


Fig. 4. E_{off} in the presence of CP and without AC.

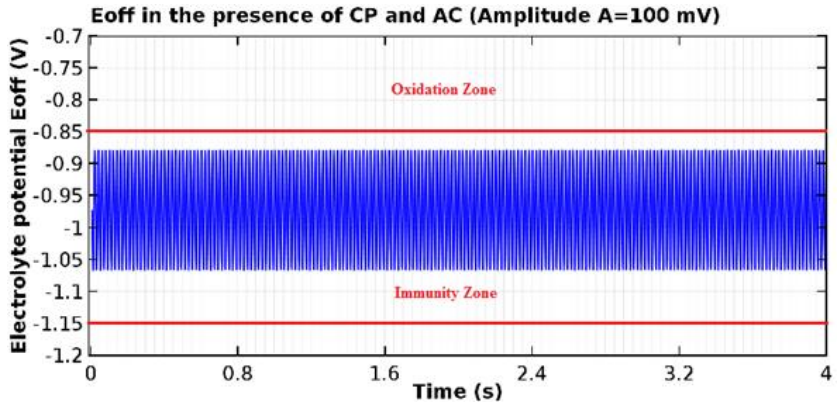


Fig. 5. E_{off} in the presence of CP and AC (amplitude A=100 mV).

Figure 4 represents the measured E_{off} in the presence of a right CP without the presence of induced current AC, we brought the E_{off} in the immunity area by choosing the adequate CP, regarding the standards [1, 3, 8, 21, 23]. Figure 5 shows that the potential E_{off} in the presence of CP and AC (amplitude A=100 mV) did not exceed the immunity zone, in this case, we did not need to modify the CP.

Figure 6 (amplitude A=200 mV) illustrates that E_{off} exceeded the immunity area, therefore there is a significant risk of corrosion. Then in Fig. 7, for the same values of AC and by introducing the resolution of the immunity program Fig. 3, we were able to bring the E_{off} in immunity zone. Secondly, we measured the concentration of the different species of the electrochemical process.

Figure 8 (amplitude A=500 mV) illustrates that E_{off} exceeded the immunity area, therefore there is a significant risk of corrosion. Then, in Fig. 9, for the same values of AC and by introducing the resolution of the immunity program Fig. 3, we were able to bring the E_{off} in immunity zone. Secondly, we measured the concentration of the different species of the electrochemical process.

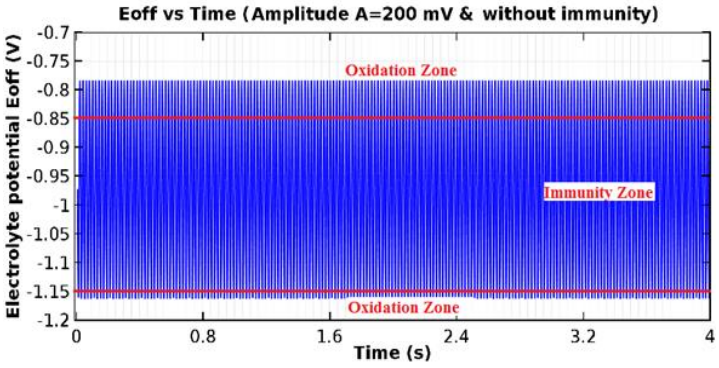


Fig. 6. E_{off} in the presence of CP and AC (amplitude A=200 mV) without application of immunity program.

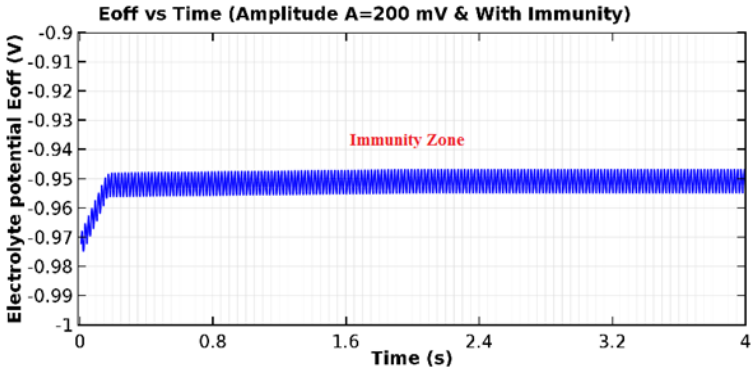


Fig. 7. E_{off} in the presence of CP and AC (amplitude A=200 mV) with application of immunity program.

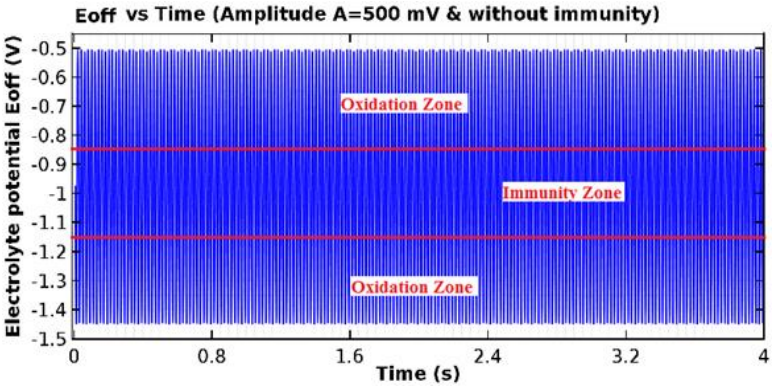


Fig. 8. E_{off} in the presence of CP and AC (amplitude A=500 mV) without application of immunity program.

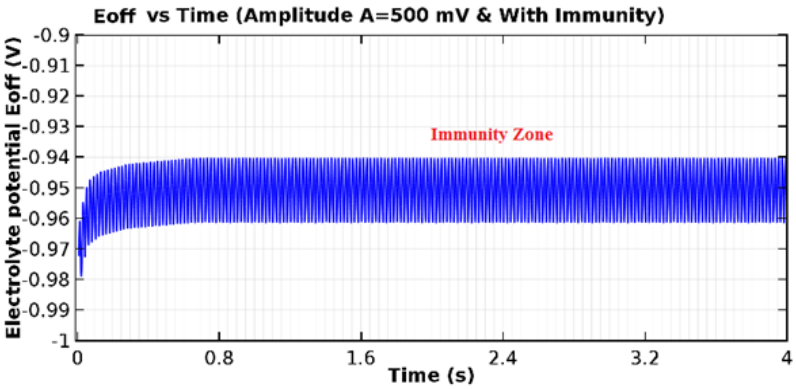
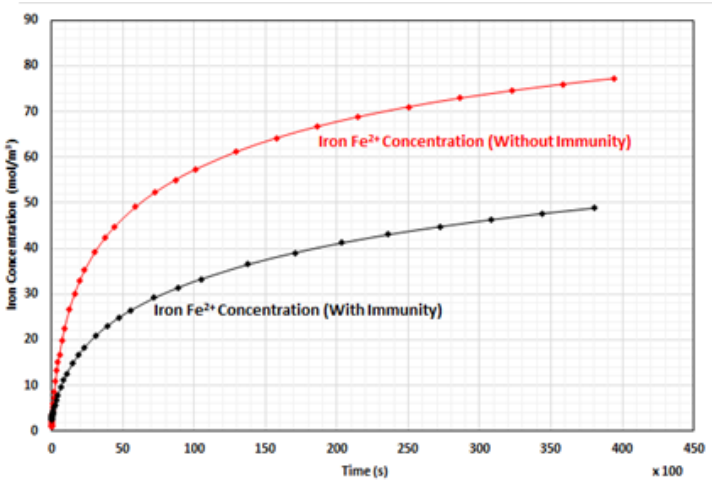


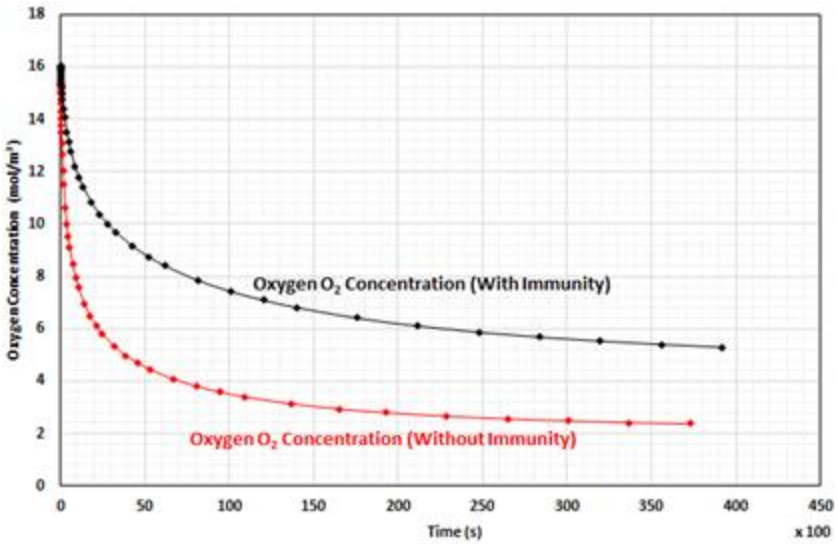
Fig. 9. E_{off} in the presence of CP and AC (amplitude A=500 mV) with application of immunity program.

4.2. The concentration of iron ions, oxygen and hydrogen

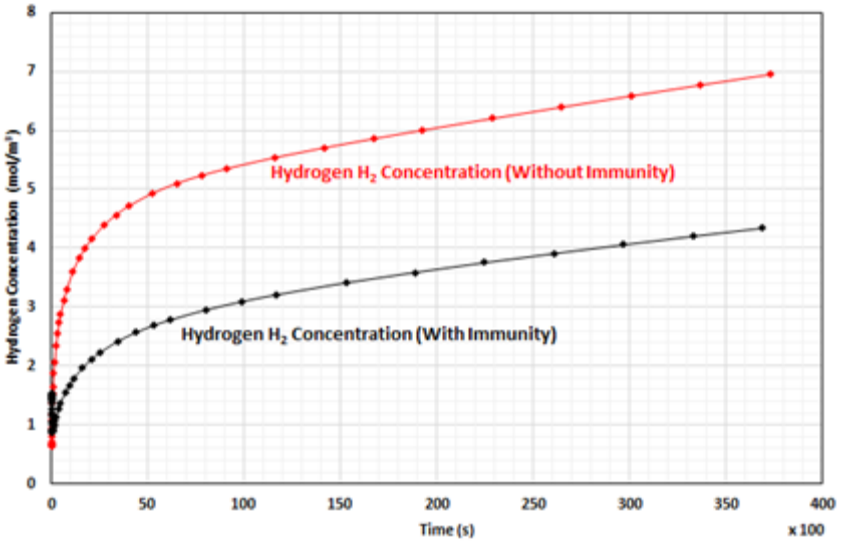
Figure 10(a) shows the increase of the iron ions Fe^{2+} concentration near the sample, thus demonstrating that a reaction of oxidation of iron Eq. (1), so the corrosion took place. And after the implementation of the immunity program Fig. 3, this concentration decrease. Figure 10(b) illustrates the important decrease of the oxygen O_2 concentration near the sample, thus demonstrating a reaction of oxygen reduction Eq. (2), so it is a case of a strong corrosion. In addition, after the implementation of the immunity program Fig. 3, this concentration increase. And Fig. 10(c) shows the increase of the hydrogen H_2 concentration near the sample, it demonstrates that it is a reaction of reduction of H_2O Eq. (3) or H^+ Eq. (4), so an important corrosion, took place. And after the implementation of the immunity program Fig. 3, this concentration decrease.



(a) Concentration of iron ions Fe^{2+}.



(b) Concentration of O_2.



(c) Concentration near sample of H_2.

Fig. 10. Concentration near sample of Fe^{2+}, O_2 and H_2.

4.3. The sample deformation under CP and AC

Finally, we studied the sample deformation protected by CP and under AC, Fig. 11 shows the restriction of the model just to view clearly the sample deformation, Fig. 12 shows a clear deformation by corrosion of the sample which was protected by CP and subjected to an induced AC, and in Fig. 13 when we apply our immunity program during the same time period (72 hours) we did not have any deformation yet.

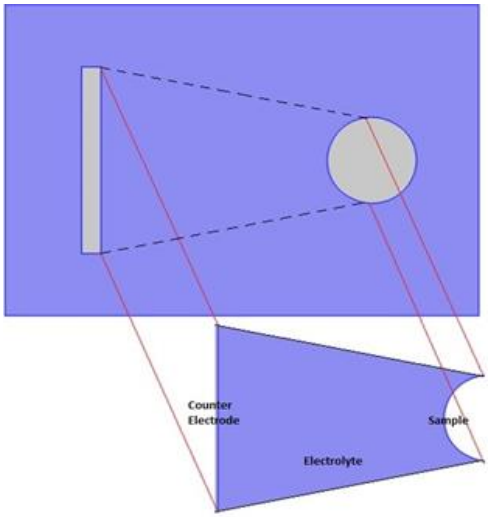


Fig. 11. Model restriction.

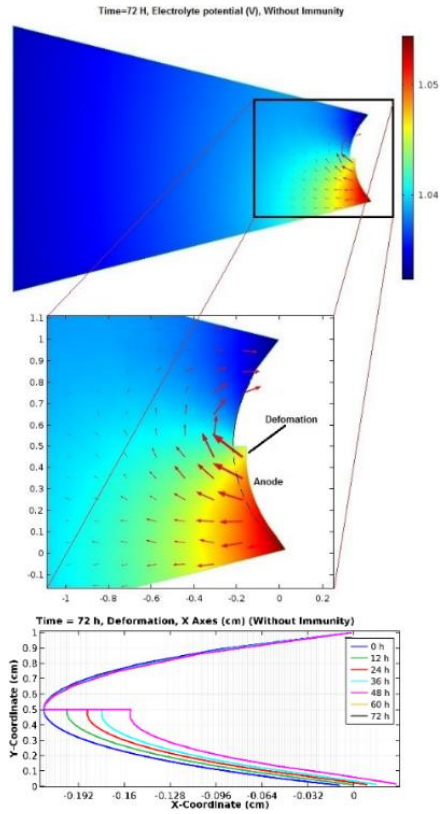


Fig. 12. Sample deformation by corrosion (under CP and AC).

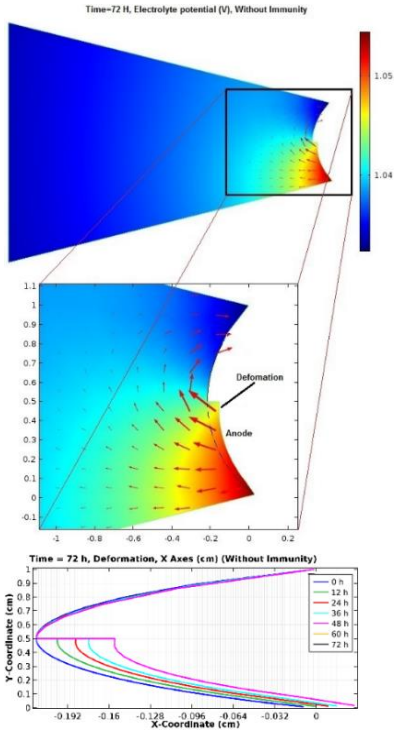


Fig. 13. Deformation state after implementation of the return program to the immunity zone.

5. Conclusions

In conclusion, regarding the numerical simulation, the results indicated that the induced AC current causes the corrosion of the sample, which was protected by the CP because we found an E_{off} exceeding the immunity zone and a strong oxidation of iron. We have also simulated the oxygen and the hydrogen concentration in the electrolyte, and the sample deformation. Then, using our monitoring program has allowed us to bring the E_{off}, in the presence of AC in corrosion immunity zone according to standards, to decrease the reactions of the electrochemical process and it equally prevents the sample's deformation.

The direct links between the experimental and simulation study are that we have used the same steel (API 5L X52); The potential applied to the studied sample obeyed to the same formula, it was equal to the addition of a direct current as a CP and an alternating current as AC interference; Results have shown that the experimental data are relatively in agreement with simulation ones; The execution of the monitoring and corrective program of CP in case that the E_{off} exceeds the limits is possible in the simulation but experimentally it is not possible by the used device, the potentiostat and galvanostat.

To sum up, in our future perspective, our goal is to establish a system provided with a microcontroller to monitor the CP and for implementing the immunity program in addition to the existing CP system in places where pipelines are near power lines and causing interference AC.

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Nomenclatures

A	Amplitude of the AC potential, mV
A_{an}	Tafel slope anodic
A_{cat}	Tafel slope cathodic
a_M	Metal activity in the electrolyte
a_M^{Z+}	Metallic ions activity
c_i	Concentration, mol/m^3
D_i	Diffusion coefficient, m^2/s
E_0	Metal standard potential, mV
E_{AC}	AC potential, mV
E_{CP}	Applied potential of CP, mV
E_{eq}	Equilibrium potential, mV
E_{off}	Reference potential, mV
F	Faraday constant, C/mol
f	Frequency, Hz
i_0	Exchange current density, A/m^2
i_l	Current density in the electrolyte, A/m^2
i_{lim}	Limiting current density, A/m^2
i_s	Current density in the electrode, A/m^2
K	Constant
M	Average molar mass
N	Flux vector, mol/(m^2.s)
N_i	Flux of species i, mol.(m^2/s)
Q_s	General current source term, A/m^3
R_i	Reaction rate expression, mol/(m^3.s)
u	Velocity vector, m/s
$u_{m,i}$	Mobility, s.mol/kg
z_i	Charge number

Greek Symbols

σ_s	Conductivity, S/m
ρ	Density of the iron
Φ_s	Electric surface potential, V
Φ_l	Electrolyte potential, V
η	Over-potential of the reaction V

Abbreviations

AC	Alternating Current
CP	Cathodic Protection
DC	Direct Current
HV	High Voltage

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