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MODELING OF THE CORROSION PROCESS IN STEEL OIL PIPELINES IN ORDER TO IMPROVE ENVIRONMENTAL SAFETY

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Розглянуто фактори, що впливають на екологічну безпеку експлуатації нафтопроводів. Розв'язана задача моделювання електрохімічної корозії трубопроводу в тріщині ізоляційного покриття при дії агресивного по відношенню до металу трубопроводу електролітичного середовища, котра зводиться до визначення стаціонарного електричного поля, що виникає при роботі гальванопари. Перевагою даної моделі є можливість прогнозування розвитку корозії сталі за часом, що є важливим при визначенні залишкового ресурсу трубопроводу

Ключові слова: сталевий нафтопровід, електрохімічна корозія, гальванічний елемент, модель корозії, швидкість корозії, екологічна безпека

Рассмотрены факторы, влияющие на экологическую безопасность эксплуатации нефтепроводов. Решена задача моделирования электрохимической коррозии трубопровода в трещине изоляционного покрытия при воздействии агрессивной по отношению к металлу трубопровода электролитической среды, которая сводится к определению стационарного электрического поля, возникающего при работе гальванопары. Преимуществом данной модели является возможность прогнозирования развития коррозии стали со временем, что является важным при определении остаточного ресурса трубопровода

Ключевые слова: стальной нефтепровод, электрохимическая коррозия, гальванический элемент, модель коррозии, скорость коррозии, экологическая безопасность

1. Introduction

Ukraine as a whole and Poltava region in particular has a well-developed network of oil pipelines, oil-product pipelines and gas pipelines whose average operation period exceeds 30 years while the first built oil pipelines have been in operation for more than 48 years [1, 2]. Prolonged interaction between pipe metal and the environment leads to the intensification of corrosion processes, to the degradation of physical-mechanical properties in the material of a pipe wall [3]. The pipelines designed and manufactured in accordance with the regulations must be resistant to the action of the environment. However, defects during manufacturing, as well as damaging, contribute to the start and development of corrosion processes in a pipeline [4]. As a consequence, the risk of emergency-dangerous defects grows, which negatively affects the environmental safety in the operation of oil pipelines. Operating the oil pipelines is inextricably linked to the corrosion damage in oil and gas equipment, including industrial pipelines. One of the ways to improve environmental safety when operating the oil pipelines in Ukraine is to take account of the factors that characterize corrosive processes in the pipelines metal, thus preventing the fracture formation at the surface and the leakage of oil [5].

Certain evaluation methods of residual resource, durability of steel transport structures that operate under conditions of aggressive media, are based on the calculations that do not account for the characteristics of corrosion processes on the sections of the design. Corrosion processes on steel sections are mostly represented by empirical dependences that are not associated with the existence of fractures in insulating coatings.

Nevertheless, it is clear that resource under the action of electrolytic solutions will be determined by the corrosion of steel in fractures that is in direct contact with the aggressive environment.

Based on the above, the task to provide for the environmental safety when operating a section of oil pipeline by monitoring electrochemical parameters of corrosion on the sections of an oil pipeline is a relevant one.

2. Literature review and problem statement

In the process of examining the oil transportation system in Ukraine, authors in [6] noted that its reliable performance and safe operation is possible only at appropriate scientific and technical provision. An issue of reliability should take up a leading place in the international and national laws. Aspects of electrochemical corrosion and features of soil corrosion, corrosive conditions in different regions of Ukraine are investigated by authors in [7]. Articles [8, 9] explored factors in the reliability of oil pipelines and resources of underground geological space of Ukraine, a process of corrosion of oil main lines under soil conditions, analyzed problems in the operation of underground facilities, condition of the line part of oil transportation system in Ukraine. Results of the scientific research point to the relevance of studies in this direction. Emergencies that arise as a result of damaging the sections of oil transportation system of the state cause significant financial and environmental losses.

The main role in assessing the environmental safety of operation under conditions of the existence of fractures in an insulating coating is attributed to examining the velocity and depth of corrosion.

The known methods for the evaluation of condition of metal by the results of corrosion tests imply the application of quantitative indicators [10, 11]. Weight coefficient of corrosion is defined as the ratio of mass loss to the sample's surface per unit of time. Depth coefficient of corrosion is used when evaluating both overall and local corrosion. Volumetric coefficient of corrosion may be determined by the volume of released gases relative to the sample's surface over a specified period of time.

When examining corrosion of steel in concrete, electrochemical methods are employed – measurement of potentials, currents, read-out of polarization curves, etc. Approximate evaluation of corrosion condition of steel is provided by the method of measuring polarization and the character of potential decay. Underlying this method is the dependence between a corrosion condition of steel, the character and speed of potential decay to the output stationary value after external anode polarization. If steel is in a passive state, then upon switching off the polarizing current, it takes a long time for the potential to return to the stationary value, and vice versa, the rapid decay of potential indicates that steel is in the active state.

Authors of [12] developed specialized software to calculate on a PC the speed of corrosion of metal by experimental data.

Taking into consideration that the corrosion of steel with fractures is of electrochemical nature, recent developments on the calculation of corrosion losses are more focused on using the electrochemical and electric parameters, such as density of corrosion current, electrode potential, polarization of metal in fractures, electrical resistance of insulating coating. The benefit here is that these parameters can be obtained directly on the structures under operation.

It is known from practical electrochemistry that finding the corrosion characteristics of metal in electrolytic medium can be reduced to determining the distribution of electric potential and current at its surface [13, 14]. This makes it possible, when studying the corrosion of steel in a pipeline in fractures, to apply general approaches to calculating a fixed electric field, which are established in theoretical electrical engineering and provisions of mathematical physics.

Much attention is paid to modeling the dependences of metal corrosion on the environmental factors and to the prediction of pipelines operating life cycle under conditions of corrosive impacts in [15, 16]. One of the first models that describe destruction of metal under the influence of the surrounding aggressive environment is the Faraday's laws.

There are also other mathematical models by other authors and scholars on the destruction of metal in pipelines under the influence of surrounding environment, but they are somewhat similar in certain aspects. This manifests itself in that the dependences of these models are empirical in nature; they include correction coefficients that are valid only for the pipelines that are not exposed to local aggressive impact. The models above, therefore, do not allow us to describe the processes of electrochemical corrosion of oil pipelines with sufficient accuracy.

Numerical studies on the behavior of steel at electrochemical corrosion are described in papers [3, 18–21], but the research did not take into account the impact of local corrosion damage and operating conditions.

Thus, even after numerous studies, the need to develop new dependences for assessing the corrosion processes that would take into account local environmental impacts, as well as special features in the operation of oil pipelines, remains largely unresolved.

3. The aim and tasks of the study

The aim of present work is to develop dependences for calculating the universal characteristic of electrochemical corrosion (electrochemical current) of an underground steel oil pipeline in a fracture of the insulating coating under the action of electrolytic medium aggressive to the metal of pipeline.

To achieve the set aim, the following tasks are to be solved:

– to devise a physical and mathematical model of electrochemical corrosion in the section of steel pipe in fractures of the insulating coating of a structure under the action of aggressive electrolytic solutions, which would be based on the real parameters obtained by a nondestructive method when inspecting the structures;

– to conduct, based on the obtained mathematical model, a theoretical study on the influence of particular parameters on the corrosion processes in steel in the fractures of an insulating coating.

4. Materials and methods for examining the modeling of local corrosion element on underground pipelines

The issue in question is of special importance in regard of oil pipelines operated with the sections in which there is damage in pipeline insulation caused by their exposure to electrolytic solutions. These areas greatly influence the development of pipeline corrosion, creating conditions for the occurrence of macro-corrosion couples. In the underground pipelines with sections with a damaged insulation, the anode and cathode polarizing characteristics of steel significantly change and, as a result, potentials of steel in these places. Given the fact that the operation of an oil pipeline with sections with damaged insulation is associated with electrochemical corrosion of pipeline metal, special attention during inspection of the pipeline should be paid to determining the characteristics of corrosion process. Current of the given galvanic couples is a universal indicator for calculating the loss of metal in the fractures.

Insulation coating as a capillary-porous material is the conductor of type 2, which is why the process of steel corrosion in it can be considered from the standpoint of typical electrochemical corrosion of metals in electrolytes.

A theory of metal corrosion considers two ways in which the electrochemical corrosion proceeds – homogeneous and heterogeneous. Most cases, which include the corrosion of pipeline in a fracture, are dominated by the heterogeneous mechanism of metal destruction. In this case, some areas at the surface of metal are the cathodes (pipeline under a layer of insulation) while the others are the anodes (pipeline in a fracture).

In this statement, a problem on electrochemical corrosion of the section in a pipeline comes down to determining the stationary electric field that occurs at galvanic couple work on the heterogeneous electrode. In other words, to recording the equations and formulas of boundary conditions that are satisfied by the potential of this field.

The basic characteristic of electric field is the potential by which one may find the density of corrosion current by the known Ohm's law in differential form:

$$i = \gamma \frac{\partial \varphi}{\partial N}, \qquad (1)$$

where γ is the electrical conductivity of electrolytic environment; N is the normal to the surface of corroded metal; φ is the potential.

Consider the electric field near a heterogeneous electrode whose model consists of 2 sections of arbitrary width, which are different in stationary potentials [2].

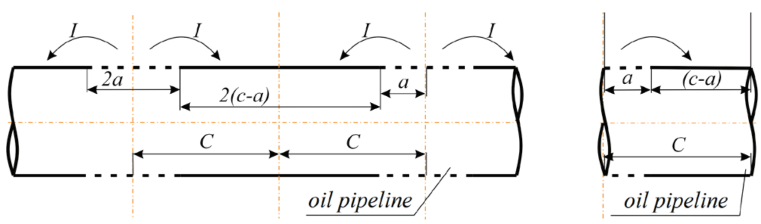
A local corrosion element is represented by the section of pipeline under an insulation coating (the cathode) and the section of pipeline in the fracture under the electrolyte (the anode) (Fig. 1).

Due to the symmetry of the model of non-uniform surface, it is sufficient to consider not the entire surface, but only part of it, between marks x=0 and x=c, which correspond to the midpoints of heterogeneous areas, and point a is the boundary between them. This part of the surface of the pipeline is from now on considered to be a local corrosion element.

Determining the distribution of electric field potential in this case can be reduced to the solution of a two-dimensional Laplace equation:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = 0, \qquad (2)$$

where φ is the potential; x, y are the flow coordinates.



a *b*

Fig. 1. Schematic of local corrosion element on a pipeline in the insulation coating with a fracture: *a* — general view; *b* — estimated model, c — distance between the midpoints of sections; 2a — width of the anode section; 2 (c-a) — width of the cathode section; 1— pipeline; 2 — insulation coating; 3 — fracture; 4 — electrolytic medium(aggressive fluid)

Boundary conditions are as follows:

1) there are no any excitations in an electric field at infinite distance from the surface of the electrode (pipeline):

$$\varphi\ (y \to \infty, x) = \text{const};$$

2) the second is the consequence of the considered model:

$$\frac{\partial \varphi}{\partial x}\Big|_{x=0} = \frac{\partial \varphi}{\partial x}\Big|_{x=c} = 0;$$

3) conditions on the heterogeneous sections will be represented in the form:

$$\varphi = E_a + L d\varphi/dy \text{ at } y=0,\ 0 \le x < a;$$

$$\varphi = E_c + L d\varphi/dy \text{ at } y=0,\ a \le x < c,$$

where $L = \gamma \cdot b$; γ is the specific electric conductivity of electrolyte; b is the coefficient of polarization; E_a, E_c are the current-less potentials of anode and cathode, mV.

Solution of equation (2) at such boundary conditions can be obtained by the Euler-Fourier method. The task is to find these functions. As a result of long transformations, we receive:

$$\varphi(x,y)=\frac{a\left(E_a-E_c\right)+cE_c}{c}+$$
$$+\sum_{K=1}^{\infty}\frac{2\left(E_a-E_c\right)}{\pi k\left(1+\frac{\pi k}{c}L\right)}\sin\frac{\pi k}{c}a\cos\frac{\pi k}{c}xe^{-\frac{\pi k}{c}y}=$$
$$=\frac{a\left(E_a-E_c\right)+cE_c}{c}+$$
$$+\frac{2\left(E_a-E_c\right)}{\pi}\sum_{K=1}^{\infty}\frac{\sin\frac{\pi k}{c}a}{\left(1+\frac{\pi k}{c}L\right)k}\cos\frac{\pi k}{c}xe^{-\frac{\pi k}{c}y} \qquad (3)$$

with regard to

$$i=-\gamma\left(\frac{d\varphi}{dy}\right)_{y=0}$$

we obtain equation for determining the distribution of current density along the surface of one of the local element:

$$i(x)=\frac{2\left(E_a-E_c\right)\gamma}{c}\sum_{k=1}^{\infty}\frac{\sin\frac{\pi ka}{c}\cos\frac{\pi kx}{c}}{k\left(1+\frac{\pi kL}{c}\right)}. \qquad (4)$$

Current density at the surface of the local element varies lengthwise. By integrating expression from 0 to a, we shall find the anode current of one element [10]

$$\int_0^a\cos\frac{\pi kx}{c}dx=\frac{c}{\pi k}\sin\frac{\pi kx}{c}\Bigg|_0^a=\frac{c}{\pi k}\sin\frac{\pi ka}{c}. \qquad (5)$$

Then the current of galvanic element is

$$I=\frac{2\gamma(E_a-E_c)}{\pi}\sum_{k=1}^{\infty}\frac{\sin^2\frac{k\pi a}{c}}{k\left(1+\frac{\pi kL}{c}\right)}$$

or

$$I=\frac{2\gamma(E_a-E_c)}{\pi}\sum_{k=1}^{\infty}\frac{\frac{1-\cos 2\frac{\pi k\alpha}{c}}{2}}{k\left(1+\frac{\pi kL}{c}\right)}. \qquad (6)$$

Thus, we solved the problem on modeling the electrochemical corrosion of steel in a fracture of the insulating coating under the action of electrolytic medium, aggressive to metal, which comes down to determining a stationary electric field of the heterogeneous electrode. The benefit of this model is the possibility to predict the development of corrosion of reinforcement over time, which is important when determining the residual resource of a reinforced concrete structure.

5. Theoretical examination of mathematical model for the corrosion of steel in a fracture of the insulating coating

According to (3), (4), the spread of potential and current density in the section of the examined pipeline that is determined by values of a, c, L and difference between stationary (current-less) potentials. This allows us to evaluate the features of electric field near the electrodes depending on the above-enumerated parameters and draw a conclusion about their impact on the distribution of potential and current.

We shall study the potential distribution at the surface of the electrode. Formula (3) at y=0 will take the form:

$$\varphi(x,y)=\frac{a\left(E_a-E_c\right)+cE_c}{c}+$$
$$+\frac{2\left(E_a-E_c\right)}{\pi}\sum_{K=1}^{\infty}\frac{\sin\frac{k\pi a}{c}\cos\frac{k\pi x}{c}}{k\left(1+\frac{\pi L}{c}\right)}. \qquad (7)$$

Function (3) is a series and it is easier to analytically examine it only in some cases, for example, at a/c=0.5 and L=c/π. A graph of function is shown in Fig. 2 in coordinates $\frac{\varphi-\varphi_{cp}}{\Delta E}$, x/c at different values of L/c.

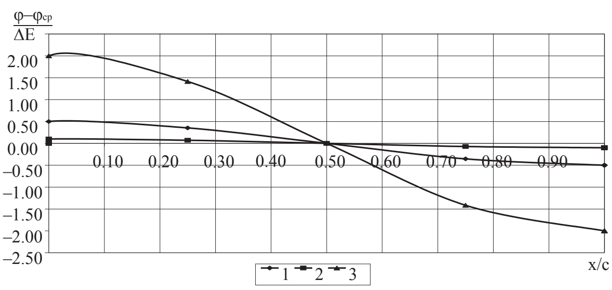


Fig. 2. Distribution of potential along the heterogeneous surface of the electrode: 1 – L/c=2.0; 2 – L/c=10.0; 3 – L/c=0.5; $\varphi_{cep}=\frac{a\left(E_a-E_c\right)+cE_c}{c}$; $\Delta E=\frac{2\left(E_a-E_c\right)}{\pi}$

If the specified parameters change, the character of distribution of potential along the surface of the electrode remains intact. Examples shown in Fig. 2 demonstrate that curve $\frac{\varphi-\varphi_{cp}}{\Delta}-\frac{x}{c}$ takes the form of a smooth step. In the region of x=a, there is a transition from one value of current density to another. At the same time, absolute difference in potentials between points x=0 and x=c depends on the polarization of metal of the reinforcement, that is, from the ratio L/c.

Given that functions (3)–(6) are a descending series, then using only the first member of the series, one may explore the influence of basic parameters on the rate of corrosion and current of galvanic couple, by conducting a numerical experiment.

Fig. 3, 4 show results of the numerical experiments, respectively, the effect of difference in the potentials and electric conductivity of electrolytic medium on the current of galvanic couple at constant a/c and L/c.

Results of examining the influence of dimensions of the sections on the current of galvanic couple are shown in Fig. 5.

Conducted analysis of a mathematical model of local corrosion element allows us to assert that the distribution of current density on the heterogeneous electrode «steel in the fracture – steel under an insulation coating» is non-uniform. The density of the anode current (speed of corrosion) is maximal in the middle of the fracture. In the region x=a, there is a transition from one value of current density to another; moreover, at larger ration L/c, uneven distribution of current density within one heterogeneous section becomes extremely low.

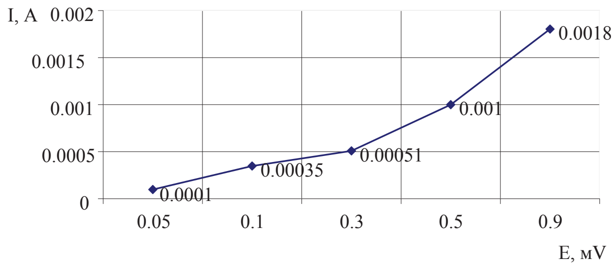


Fig. 3. Dependence of corrosion current on the difference in stationary potentials in the anode and cathode sections at $\gamma=0.067,\ \frac{L}{c}=10;\ \frac{a}{c}=0.25$

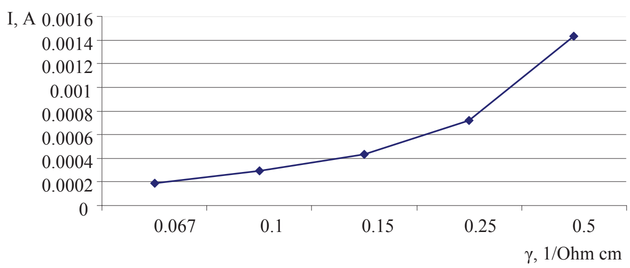


Fig. 4. Impact of electric conductivity of electrolytic medium on the corrosion current at $\Delta E=0.290$, $L/c=10$, $a/c=0.25$

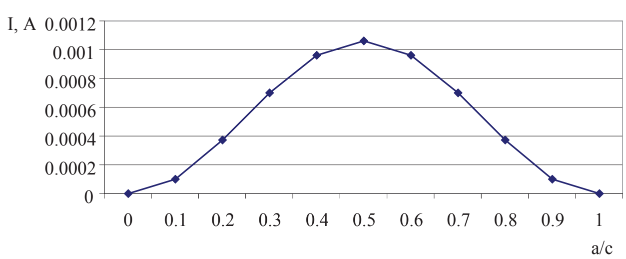


Fig. 5. Dependence of the current of galvanic couple on the ratio a/c: $\Delta E=0.3$; $L/c=10$; $\gamma=0.067$

With an increase in the anode area, maximal spread in current density between different sections is reduced, whereas the non-uniformity of its distribution within the same area increases. The effect of dimension of the anode area (width of fracture) in the current distribution on the heterogeneous electrode considerably exceeds its own size.

The main impact on the magnitude and distribution of potential and the speed of corrosion is exerted by the difference in potentials at the heterogeneous surface between the cathode and anode areas and electrical conductivity of the medium.

The rate of corrosion on the heterogeneous electrode increases with increasing difference in potentials between the sections of «pipeline in the fracture – pipeline under an insulation coating» and increasing electrical conductivity of the medium in which a galvanic couple operates.

At a decrease in the polarization characteristics of metal in reinforcement under corrosion environment, non-uniformity in the distribution of potentials and the speed of corrosion on the heterogeneous electrode (reinforcement) grow. The uniformity of distribution of the corrosion speed is affected also by the ratio of dimensions of the anode sections to the cathode ones.

6. Discussion of results of examining a mathematical model for the corrosion of steel in a fracture of the insulating coating

Experimental studies demonstrated that the main role in the corrosion processes on a steel pipeline in the fracture of an insulation coating exposed to aggressive solutions belongs to the work of macro galvanic couples «metal of pipe in the fracture – metal of pipe under an insulation coating». The current of given galvanic couples is a universal indicator for calculating the loss of metal in fractures.

The dependence received allows us to calculate the depth of corrosion damage, and hence the thinning of wall of a pipeline in the fracture of an insulation coating during work of macro galvanic corrosive couples and stable stay of aggressive solution in the fracture.

The dependence includes parameters, which can be obtained directly based on the measurements on real structures, by the data contained in the design documents at the time of examination. Calculations based on the constructed dependence make it possible to detect the most dangerous areas of critically important damage to an oil pipeline and thus reveal location of particular ecological danger to the environment.

The benefit of this model is a possibility to predict the development of corrosion over time regardless of the chemical composition of an aggressive electrolyte, the possibilities of obtaining the required estimated parameters about structures under operations by a non-destructive technique. A discrepancy between results of the experimental data and those calculated by the proposed mathematical model amounted to 11 % on average.

Based on the developed model of the electrochemical corrosion of a pipeline section in the fracture of an insulation coating, we plan to devise a technique for evaluating the residual resource of pipeline sections by bearing capacity and by suitability for further use.

7. Conclusions

Modeling of electrochemical corrosion of steel in a pipeline section in the fracture of an insulating coating is reduced to determining the stationary electric field that occurs during work of a macro galvanic couple. Distribution of electric field potential is determined by solving a two-dimensional Laplace differential equation.

The advantage of this model is the possibility to predict the development of corrosion over time, obtaining the required estimated parameters on structures under operation, by a non-destructive technique. A discrepancy between results of the experimental data and those calculated by the proposed mathematical model is 11 % on average.

Calculations by the model in question allow us to predict corrosion losses of metal in a pipeline in the fractures of insulation coating exposed to aggressive electrolytic solutions regardless of their chemical composition.

The main impact on the magnitude and distribution of potential and the rate of corrosion is exerted by the difference in potentials at the heterogeneous surface between the cathode and anode areas and electrical conductivity of the medium. The speed of corrosion on the heterogeneous electrode increases with increasing difference in potentials between the sections «steel in the fracture – steel under isolation» and growing electric conductivity of the environment in which a galvanic couple operates.

At a decrease in the polarization characteristics of pipeline metal in the corrosive medium, non-uniformity in the distribution of potentials and the rate of corrosion on the heterogeneous electrode increases. The uniformity of distribution of the corrosion speed is also affected by the ratio of dimensions of the anode and cathode areas.

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