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Research paper

Calculation of Steel Pipeline Corrosion Depth for Various Conditions of Electrolyte Solutions in Cracks

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Abstract

On the basis of the electrochemical corrosion mathematical pipeline model in the insulating coating crack under the action of an aggressive electrolytic medium towards the pipeline metal, the dependence was obtained that allows to calculate the pipeline wall corrosion depth of the during the work of macro-galvanic corrosion couples in the conditions of stable and periodic stay of the aggressive solution in the damaged zone. The advantage of this model is the ability to predict the corrosion development over time regardless the corrosive electrolyte chemical composition, the possibility of obtaining necessary design parameters for operated structures. The developed dependencies of the pipeline section corrosion depth make it possible to plan rationally the repair work, to predict the structure work real terms, to review the operation mode, etc. The obtained results allow us to more reliably evaluate the bearing capacity of structures that operate in conditions of aggressive medium with cracks.

Keywords: *steel oil pipeline, electrochemical corrosion, galvanic element, corrosion rate, corrosion depth, residual life*.

1. Introduction

Ukraine has a developed network of main oil pipelines, petroleum product pipelines and gas pipelines, their average life being more than 30 years. The first built oil pipelines have been operating for more than 48 years [1, 2]. The long-term interaction of the metal pipe with the environment leads to the intensification of corrosion processes, to the degradation of the wall material physical and mechanical properties of the steel pipe [3].
The lifetime of Ukrainian main gas and oil pipelines system is in many cases approaching the planned one. The numerous corrosion damage of the outer surfaces of pipes has been found that aggravates further reliable and safe operation.
Oil pipelines operate under influence of various factors, which include temperature fluctuations, corrosive - aggressive media with a wide spectrum of their parameters, dynamic loads, etc. The most negative influence on the life of pipelines is corrosion - aggressive media [4, 5, 6]. Corrosion-hazardous sections regardless of the medium corrosive aggressiveness indicators and the presence of earth currents include: floodplain; irrigated land; swamps and waterlogged soils; underwater transitions; industrial and household drains; rubbish and slag dumps; field warehouses of mineral fertilizers [7]. Corrosion may be aggravated by the occurrence of galvanic couples in the case of alternation of different composition soils under the temperature influence factors, technology-related human activity, due to the development of microbiological organisms.
The analysis of the causes of pipeline failures shows that the most frequent damage of steel tubes are blowholes, caused by corrosion of pipes [8, 9]. The process of working out the design service life takes place against the backdrop of the metal pipe electrochemical corrosion development, which causes a decrease in the wall thicness, and therefore a gradual decrease in the structural life.
The question of evaluating the actual technical condition of technological equipment and pipeline networks in the oil and gas industry is particularly relevant because of the need to extend the life of the objects that have finished off their guideline life, as well as to ensure reliable and safe operation of such facilities [10].
As it was proved by Severnev M. M. [6], in the case of two-sided corrosion, the average losses per year for carbon steels are ~140 g / m2, which corresponds to a value of 0.035 mm, for processes of corrosion damage development, the speed is insignificant, while actual and necessary consideration is given to the possibilities of local corrosion, as well as other types of corrosion damage development. Especially dangerous is the combination of corrosion and mechanical factors, because their joint action may result in corrosion cracking, corrosion fatigue and fretting oxidation.
One of the ways to improve environmental safety and durability of oil pipeline exploitation is taking into account factors that characterize corrosion processes on metal pipes, thus preventing the formation of cracks on the surface and oil leaking.
Some methods for assessing the residual life and durability of steel transport structures that work in aggressive environments are based on calculations that do not include characteristics of corrosion processes in sections of structures. Corrosive processes in steel sections are mainly presented by empirical relationships that are associated with the presence of cracks in the insulating coating.

Proceeding from the above-said, the ecological safety provision of the oil pipeline section exploitation by monitoring the corrosion electrochemical parameters in the pipeline sections is relevant. The issue of residual life of existing steel pipes correlates to the definition of pipeline wall thickness. The urgency of such tasks is beyond doubt in many regions of the world. Moreover, one of the priorities of the XXI century priorities is the problem of environmental safety and environmental monitoring. Hence, the main task is to provide the reliability and safety of pipeline systems.

2. Main body

When studying the oil transportation system of Ukraine, authors [11] noted that its reliable work and safe operation is possible only with appropriate scientific and technical support. The reliability problem should take the main place in international and national legislation.

In the works [12, 13] the reliability factors of oil pipelines and resources of the underground geological space, the corrosion process of main oil pipelines in soil conditions were investigated, operation problems of underground objects, the state of the oil transportation system linear part, in particular, in Ukraine, were analyzed. The results of studies point to the research line importance.

As it is known, the reliability of pipelines is formed at the design stage. The structural strength calculation on the basis of the building mechanics methods with the use of stock factors cannot fully take into account the variety of the structure operation conditions.

Application of aerospace methods for controlling the condition of the pipeline, the magnetic and ultrasonic flaw inspection pigs of the new generation definitely gives a picture of the structure actual state, and allows to prevent the possible emergency situations. On the other hand, to carry out such monitoring is quite costly.

Periodic diagnostic survey of oil pipelines allows to predict the growth of the corrosion damage depth and to prevent possible emergency situations at certain linear sections [14].

The main role under providing the environmental safety of pipeline operation in the development of corrosion damage (cracks) belongs to the study of corrosion depth and dynamics.

There is a known method [15] for forecasting the dynamics of the pipeline corrosion depth, which is carried out on the basis of two or more measurements of the wall thickness according to the formula

$$\Pi_e = \frac{365\sum_i \Delta S_1 + \Delta S_2 + \cdots + \Delta S_n}{n T_e} \quad (1)$$

where Π_e is corrosion speed in the section of the pipeline which is controlled in the operation conditions, mm / year;

ΔS is the difference of wall thicknesses at points in the period of control measurements mm, indexes 1, 2, ... n denote control point numbers;

T_e is the operation time between the control measurements, days;

n is the number of measurement control points (not less than three).

However, this model does not take into account the corrosion process conditions.

The authors [16] use the expression to determine the wall thickness and calculate the corrosion depth

$$\ln \Delta S = \alpha - \beta T^{-1} + (\gamma + \varepsilon T)\ln \tau, \quad (2)$$

where ΔS is corrosion depth per hour τ, mm (mm),

τ - is time, (hours)

T - is an absolute temperature of metal on the pipe surface, K,

α, β, γ, ε are coefficients depending on the material of the pipes, the type of raw materials, etc.

Such methods for assessing the corrosion depth damage on sections of transport structures that operate under aggressive media are based on calculations that do not take into account the characteristics of corrosion processes. Corrosive processes in steel sections are mainly represented by empirical dependencies, which are not associated with the availability of cracks in the insulating coatings.

In publications containing the description of methods for calculating the corrosion wear rates on the basis of operational control data, it is noted that the calculation is empirical. In the investigated methods, factors that considerably increase the calculation error [17-21] are taken into account.

Scientists have proven that the main role in assessing the safety of pipeline operation in the presence of cracks in the insulating coating belongs to the study of the corrosion speed and depth.

Well-known methods for assessing the metal state by the results of corrosion tests suggest the use of quantitative indicators [22, 23]. The weight corrosion index is defined as the ratio of mass loss to the sample surface per unit time. The deep corrosion rate is used for the assessment of both continuous and local corrosion. The actual corrosion rate can be determined by the volume of the evolved gases relatively to the surface of the sample for a definite period of time.

Taking into account that the corrosion of steel with cracks is electrochemical, recent developments, on calculations of corrosion losses, are more oriented to the use of electrochemical and electrical parameters such as corrosion current density, electrode potential, metal polarization in cracks, electrical resistance of insulating coating. The advantage here is that these parameters can be obtained directly from the structures that are being in operation.

The way to accident-free operation of the pipeline technology can be in monitoring and controlling the electrochemical parameters characterizing the development of steel electrochemical corrosion process.

The practical electrochemistry says that the search for corrosion characteristics in a metal in the electrolytic medium can be reduced to the determination of the electric potential and current distribution on its surface. This makes it possible, when investigating pipeline steel corrosion in cracks, to use general approaches to calculations of stationary electric fields, which are developed in theoretical electrical engineering and sections of mathematical physics.

Hence, despite numerous studies, the need to develop new dependencies for the assessment of corrosive processes that take into account local environmental influences, special features of the exploitation of underground steel pipelines, remains relevant.

The purpose of this work is to develop dependencies that allow to calculate the loss of the cross section in the insulating coating crack under the action of an aggressive electrolytic medium towards the metal pipeline.

To achieve this goal the following tasks were solved:

- on the basis of the local corrosion element mathematical model to develop a dependence that will allow to calculate the steel pipeline corrosion depth in the insulating coating crack, which would be based on real parameters obtained during the examination of structures;
- to develop a method for calculating the pipeline section corrosion depth in the insulating coating crack in the conditions of the aggressive solution periodic action, which is focused on the periodic monitoring of electrochemical parameters in real structures.

The metal pipe long-term interaction with environment leads to the intensification of corrosion processes, to the degradation of physical and mechanical properties of the pipe wall material [3]. Pipelines designed and manufactured in accordance with the requirements of the normative documents must be resistant to the environment. However, defects in the manufacture and damage contribute to the beginning and development of pipeline corrosion processes [4]. As a result, the risk of accident hazards increases, which adversely affects the environmental safety of the operation of oil pipelines. Exploitation of oil pipelines is inextricably linked with the corrosive destruction of oil and gas equipment, industrial pipelines, in particular.

The study of the operation conditions of pipelines in the soil environment shows that, despite the use of various measures, the number of pipeline accidents due to corrosion is about 27% of the total.

An important factor in providing the accident free operation of underground oil pipelines is the protection of their surface from soil corrosion with high-quality insulating coatings. Among the wide range of insulating materials, the dominant positions in the oil and gas complex of Ukraine belong to less effective in terms of anticorrosion but cheaper mastic coatings on the petroleum bitumen basis. Though, in the course of their operation, there is a significant damage to the insulating coatings.

The frequent defects of the insulating coating are rust-through damage and insulation layer separation.

In underground pipelines with sections where insulation is damaged, the anode and cathode polarization characteristics of steel are significantly changed, and as a consequence, the steel potentials in these points. Such sections greatly influence the pipeline corrosion development, creating the conditions for the emergence of macrocorrosion couples. In view of the fact that the exploitation of the oil pipeline with sections where the broken insulation is provided with the metal pipeline electrochemical corrosion, attention should be given to the corrosion process characterization when examining the pipeline. The current of galvanic coupling data is a universal indicator for calculating metal losses in cracks.

So article is devoted to the question of calculating the corrosion damage degree of the pipeline section, namely, the definition of the corrosion damage depth due to the electrochemical corrosion development.

Being a capillary-porous material, insulating coating is a second class conductor, therefore the steel corrosion process in it can be considered from the standpoint of ordinary electrochemical corrosion of metals in electrolytes. In most cases, which can include the pipeline corrosion in the crack, the heterogeneous mechanism of the metal destruction prevails. Herewith, certain parts of the metal surface are cathodes (pipeline under the insulation layer), and the other - anodes (pipeline in the crack).

The main characteristic of the electric field is the potential for which it is possible to find the corrosion current density according to the known Ohm law in the differential form:

$$i = \gamma \frac{\partial \varphi}{\partial N}, \tag{3}$$

where γ – is the electrolytic medium electrical conductivity;

N - is the normal line to the corrosive metal surface;

φ is the potential.

Let us consider an electric field near a heterogeneous electrode whose model consists of 2 sections of arbitrary width that differ in stationary potentials.

The local corrosion element is represented by a pipeline section under an insulating coating (cathode) and a section with a pipeline in a crack under an electrolyte (anode) (Fig. 1)..

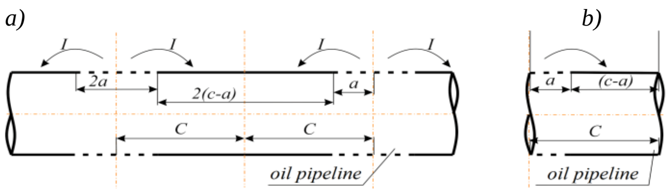

Fig. 1. Scheme of a local corrosion element on a pipeline in an insulating coating with a crack: a - general form; b - calculation model, c - distance between the middle of the sections; 2a - width of the anode section; 2 (c - a) - width of cathode section; 1 - pipeline; 2 – insulating coating; 3 - crack; 4 - electrolytic medium (aggressive liquid)

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

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = 0, \tag{4}$$

where φ is the potential;

x, y are the current coordinates.

The solution of equation (4) under certain boundary conditions can be obtained by the Euler-Fourier method and taking into account that

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

we obtain an equation for determining the current density distribution on the surface of a single local element:

$$i(x) = \frac{2(E_a - E_k)\gamma}{c} \sum_{k=1}^{\infty} \frac{\sin\frac{\pi k a}{c}\cos\frac{\pi k x}{c}}{k(1+\frac{\pi k L}{c})} \tag{5}$$

The current density on the local element surface varies in length. Integrating the expression from 0 to a, we find the anode current of a single element [24]:

$$I = \frac{2(E_a - E_k)\gamma}{\pi} \sum_{k=1}^{\infty} \frac{\frac{1-\cos 2\frac{\pi k a}{c}}{2}}{k(1+\frac{\pi k L}{c})} \tag{6}$$

Thus, the problem of modeling the steel electrochemical corrosion in the crack of the insulating coating during the action of an aggressive metal electrolytic medium, which comes down to the determination of the heterogeneous electrode stationary electric field, is solved. The advantage of this model is the ability to predict the valve corrosion development over time, which is important in determining the reinforced concrete structure residual life.

The pipe wall thickness is one of the main parameters that affects the changes in the stress-strain state of the structure, but also, therefore, on its residual life. The pipeline cross-section changing leads to a change in the distribution of stresses in the pipeline and contributes to the development of environmentally hazardous situations. The pipe wall thickness depends on the working pressure of loads, structural characteristics and strength redundancy, including allowance to uniform corrosion loss.

In order to calculate the cross section area loss under the constant being of an aggressive electrolytic solution in the damaged insulation zone, the pipeline corrosion depth dynamics during the operation of the galvanic element "pipeline having damaged insulation - the pipeline under the insulating coating" is considered [25].

$$h = \frac{V}{\pi D_0 a_y} = \frac{KIt}{7,87\pi D_0 a_y} \tag{7}$$

where V is the volume of the corroded metal in the crack, cm3;

D_0 is the initial diameter of the reinforced bar, cm;

K is the electrochemical equivalent, g / A h;

t – is corrosion time, h.;

7.87 –is specific gravity of metal reinforcement density, g / cm3;

I – is galvanic couple current, A;

a_y is the of the valve section length under the normal crack to be damaged, cm.

Consequently, taking into account (5) from formula (6), we have

$$h = \frac{K}{7,87\pi D_0 a_y}\left(\frac{2(E_a - E_k)\gamma}{\pi}\sum_{i=1}^{\infty}\frac{\frac{1-\cos 2\frac{\pi k a}{c}}{2}}{k(1+\frac{k\pi L}{c})}\right)t\,. \tag{8}$$

The frequency of penetration into the crack of an aggressive solution will affect the hourly average current strength of the galvanic couple, and hence the steel corrosion rate in the crack.

The hourly average current strength increases with the increase in the frequency of penetration aggressive solution into a crack, but until the cathodic limitation of the process occurs, as solution saturation stops the oxygen inflow.

The pipeline section corrosion in the crack reaches the most active phase when on its surface a moisture film is formed. Herewith, the moisture film thickness is that the anode process in it is not yet slowed down, and there are the most favorable conditions for the cathode process development in the pipeline section under the insulation coating.

On the basis of the above said it is possible to assume that the steel corrosion process in the cracks of insulating coatings is a special kind of electrochemical corrosion, where the features of both atmospheric and electrochemical corrosion of steel which is completely immersed in a liquid electrolyte are manifested.With regular periodic moisturization, it is possible to predict further steel losses proceeding from the next calculation.

The instantaneous wall thickness loss $V = \Delta D / \Delta t$ is defined as the limit of the average velocity, provided that the time interval Δt is unlimited, that is,

$$V = \lim \frac{\Delta D}{\Delta t} = \frac{dD}{dt} \quad (9)$$

Thus, the velocity of change in the pipeline wall thickness is the time derivative of the initial wall thickness size. It is also clear that the rate of change in the wall thickness will be proportional to its size.

Consequently, the dependence of the change in the wall thickness of the pipeline section from time t can be regarded as a derivative in time

$$\frac{dD}{dt} = -rD \quad (10)$$

where r – is the relative rate of wall thickness decrease, which depends on the grade of steel, the original wall thickness aggressiveness of environment.

After integration we get

$$\ln D = -rt + \ln a$$

where integration constant $A = \ln a.$

From the last equation after exponentiation we have

$$D = ae^{-rt} \quad (11)$$

If the initial thickness of the wall of the pipeline $D = Do$ is known at the initial time $t = 0$ (at the beginning of the structure operation), then substituting these values in (11), we obtain:: $D_0 = a \times e^{-r\times 0}$, from which $a = D_0$

Then (11) is

$$D = D_0 e^{-rt}. \quad (12)$$

To determine r (specific velocity of wall thickness reduction), we take logarithm of the both parts of equation (12)

$$\ln D = \ln D_0 - rt. \quad (13)$$

Using equation (13) it is possible to calculate the values of r for two known values of the cross sections $D1$ and $D2$.

The thickness $D1$ is determined at the time of the tests t_1 at the maximum current of the galvanic couple (when moistening), and the thickness $D2$ is determined by the time t_2 before the next wetting when the stable minimum value of the galvanic couple current is reached

$$D_2 = D_0 e^{rt_2}. \quad (14)$$

Then:

$$\ln D_1 = \ln D_0 - rt_1,$$
$$\ln D_2 = \ln D_0 - rt_2. \quad (15)$$

We subtract the second equation of system (15) from the first one

$$nD_1 - \ln D_2 = -rt_1 - (-rt_2) = r(t_2 - t_1)$$

from which

$$r = \frac{\ln D_1 - \ln D_2}{t_2 - t_1} \quad (16)$$

Consequently, the formula (12) can be written as follows:

$$D = D_0 e^{-\left(\frac{\ln D_1 - \ln D_2}{t_2 - t_1}\right)t}. \quad (17)$$

The pipeline wall thickness in the crack after the time interval t_1 is

$$D_1 = D_0 - \frac{2KI_1}{7{,}87\pi D_0 a_y} t_1. \quad (18)$$

Similarly, it is possible to find the wall thickness after the time interval t_2

$$D_2 = D_0 - \frac{2KI_2}{7{,}87\pi D_0 a_y} t_2. \quad (19)$$

The residual wall thickness of the pipeline at any time t from the operation beginning or preliminary examination is

$$\Delta D = D_0 - D_0 e^{-\left(\frac{\ln D_1 - \ln D_2}{t_2 - t_1}\right)t}, \quad (20)$$

or

$$\Delta D = D_0 (1 - e^{-\left(\frac{\ln D_1 - \ln D_2}{t_2 - t_1}\right)t}).$$

In the case of irregular periodic moisturization of the structure, steel corrosion calculations are also performed according to the average value of the galvanic couple current average value.

On the basis of the sample data of the measurements, the average current value, the mean square deviation, are found, and further, assuming that the law of the sample data distribution is normal, with a probability of 0,997, according to the rule of "three sigmae", the mean value of scattering limits is obtained:

$$\varepsilon = \bar{I} \pm 3\sigma,$$

where: I –is the average value of galvanic couple current;

σ -is the mean square deviation.

On the basis of the developed mathematical model of the galvanic corrosion element work in the steel pipeline section, the dependence is obtained that allows us to calculate the corrosion damage depth of the pipeline section with a constant and periodic penetration of an aggressive electrolytic solution into the damaged insulation area.

Dependencies make it possible to predict the corrosion development in time, regardless the aggressive electrolyte chemical composition, the possibility of obtaining the required calculation parameters from the structures which are used.

By studying the dynamics of the pipeline section loss in the insulating coating crack, it is planned to develop a methodology for assessing the residual life of the pipeline sections for bearing capacity and suitability for further operation.

3. Conclusions

Based on the mathematical model of the local corrosion element

work, the dependence has been developed that allows calculating the loss of the cross-sectional area of the steel pipeline in the insulation coating crack under different conditions of the aggressive solution penetration. Dependencies are based on real parameters obtained by a non-destructive method during the structure examination. The calculation study of the cross-sectional area relative loss of the steel pipe during its corrosion in the crack of the insulating coating showed that direct corrosion tests are compliant with the current values of the macro-galvanic couples.
The developed dependencies of the pipeline cross- section area losses make it possible to plan rationally the repair work, to predict the real terms of the structure work, to review the operation mode, etc. The obtained results allow us to more reliably estimate the bearing capacity of cracked structures operating in aggressive media conditions.

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