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CORROSION MODELING IN DEFECT ON PIPELINE METAL SURFACE TAKING INTO ACCOUNT THE SEASONAL CHANGE OF TEMPERATURE

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ABSTRACT

We offer a model for predicting the dependence of the corrosion rate of steel on temperature. Increasing the temperature, decreases the molecular ion oxygen overstress and increases its diffusion rate to the metal surface, which ultimately leads to an increase in the corrosion rate.

We consider corrosion in a surface defect of a type of crack. The initial conditions, the activation energy of the corrosion process of steel in aqueous NaCl solution are taken into account. We use the generalized Kaeshe type relation for corrosion current, which includes: electrolyte conductivity, potential difference, crack opening and depth, parameter Tafelin corrosion current and metal corrosion potential, specific energy of plastic deformation of the surface (interphase) layer during the formation of a new (juvenile) surface. Additionally, to describe the pitting corrosion of steel, we apply the diffusion and mass transfer equations.

The Kaesche type ralation for the anode current density in the defect on the surface of the underground pipeline has been improved, taking into account the cathodic protection potential.

The basic relations of a new mathematical model that can be completed by the stress corrosion cracking of a metal pipe made of steel near an oil pumping station are formulated.

The new model is based on an improved Kaesche type relatio for anode current density, a new criterion for metal strength, a method for estimating the boundary condition of a pipe-pressured steel tube, and an optimization approach using neural networks. These relatios are the basis of a mathematical model for investigating the effect of temperature on the rate of corrosion process on a steel surface.

***KEY WORDS**: steel, metal of pipeline, strength criterion, surface defect, crack, mathematical model, corrosion rate, effect of temperature, corrosion current, plastic deformation, Kaeshe type relation.*

INTRODUCTION

Pipes are made of steel, in particular, for underground oil pipelines. The efficiency of the respective transport companies depends on the thermal regimes of the oil pipelines. Oil pipeline crashes are concentrated at a distance of up to 30 km after oil pumping stations (OPS). Corrosion processes occur on the surface of underground pipes and are promoted by soil moisture in places of damage to insulation.

As a result of corrosion, caverns and cracks are formed on the surfaces of the pipes. Crack fracture eventually ends with stress corrosion cracking (SCC).

In this context, it is advisable to analyze the dynamics of the SCC and develop recommendations to take into account the influence of thermal modes of steel structures (SC). The control of thermal modes of SC will allow to optimize the technological process of functioning of underground metal pipelines to prevent their damages, which is an important problem because SCC leads to catastrophic consequences.

The intensity of corrosion processes on the metal surface (in particular steel) depends on the temperature [1]. Temperature effects on the metal surface in corrosive media were considered in [2]. In scientific articles [3, 4] elements of modeling of thermal effects in underground metal structures in contact with soil electrolyte are proposed. Important in this context is the study of changes in corrosion current in surface defects of crack type metal [5-7].

The change in pipeline metal temperature caused by the operation of compressor and oil pumping stations (OPS) is seasonally manifested [8]. Such changes are accompanied by the influence of heat on the contacting soil layer and on the moisture in it. The corresponding changes provoke the development of SCC in underground pipelines. It is also known that the diffusion of oxygen through the soil layer along the perimeter of the pipe will be variable due to temperature [8]. It also affects the corrosion rate of the metal. In the complex, the consideration of the above two effects has not been considered in scientific publications on electrochemistry.

In addition, stress analysis shows that stress corrosion develops from the outer surface of the pipeline. Corrosion stress fractures (CRC = SCC) are provoked by local corrosion; cracks originate from caverns, pits [8]. Therefore, a proper description of the two effects (seasonal effects on metal temperature and soil oxygen diffusion) in the presence of corrosion cracked coffee is an important scientific problem. His study will allow us to correctly model the corrosion (anode) current and to predict the development of SCC, as well as to estimate the life of the pipeline with a corrosive cavern.

The purpose of the study is to simulate the density of corrosion current (corrosion rate) in a crack-like defect on the surface of an underground metal pipeline, taking into account the seasonal temperature change. The achievement of the stated goal involves the following tasks:

- prepare corrosion current information for two values of maximum temperatures at the metal surface (near the OPS): $T_1 = 333$ K (summer), $T_2 = 313$ K (winter).

– to formulate a correlation of a new mathematical model for analyzing the effect of seasonal changes in temperature on corrosion processes and stress-corrosion cracking (SCC) of steel pipe metal near the OPS.

MATERIALS AND METHODS

According to the methods [9, 10], taking into account artificial neural networks (ANN) [11, 12], it is proposed to control the deviations of currents and voltages obtained as a result of diagnosing surveys of the section of the underground pipeline by means of БВС (contactless current meter) and PPM (the polarization potential meter). It is also proposed to use a technique for predicting the metal resource of a pipeline with a surface cracked defect, taking into account the hydrogen index of the soil electrolyte at the metal boundary [9, 11, 12].

For a pipe weakened on the outer surface by a defect of the cavern type with depth h, at the top of which there is a crack with depth c, we write the relation for the internal critical pressure [12, 13]:

$$p_{cr} = \frac{8 \cdot d \cdot \sigma_T}{3\sqrt{3}\left(\sqrt{2}+1\right)K_t \cdot R} \cdot \frac{(1{,}5 + K_Z)\cdot(r_C + c)^4}{(r_C + c)^4 + 0{,}5 \cdot r_C^2 (r_C + c)^2 + r_C^4} , \tag{1}$$

where
$$K_Z = \left(\frac{d-c}{2} \cdot \frac{2(d-c)+3r_C}{d-c+r_C} - \frac{3d}{2K_t} \right) / \left(\frac{d}{K_t} + \frac{r_C}{3} \cdot \left(\frac{r_C^3}{(d-c+r_C)^3} - 1 \right) \right);$$

p_{cr} – is the limit value of the internal pressure during which a zone of plastic deformation appears at the crack tip); σ_T – is the metal yield strength; $D = 2R$, R, d is the diameter, radius and thickness of the pipe wall; K_t – is the stress concentration factor; r_C – is the radius of curvature of the surface at the crack tip.

The critical pressure p_{cr} corresponds to the condition of reaching the fracture (plastic) state at the crack tip according to the fluidity criterion, in particular, of Huber-Mises-Hencky [12].

For estimate the current density in the cavern and around the crack tip [12], we use the generalized Kaeshe relation type:

$$I_a = I_0 \cdot \left(\exp\left(\frac{DE}{a} \right) \right) \cdot \left(1 + \beta_W \cdot W_{PL}\right); \qquad I_0 \cdot = \frac{\alpha \cdot \chi \cdot \Delta\psi_{ak}}{\delta \cdot \ln\left(\left(h + c + r_C\right)/\delta\right)}, \tag{2}$$

where a is the Tafel parameter of the anode metal dissolution process; $DE = E_0 - E_a$;
I_0, E_0 – corrosion current density and corrosion potential of metal;
I_a, E_a – is the anode current density and the anode potential for metal.
δ - crack opening; α is the angle at the crack tip; χ is the electrical conductivity of the electrolyte;
$\Delta\psi_{ak}$ – k is the ohmic change of potential between the anode and cathode parts (anode - top, cathode - crack sides); $h+c+r$ - total depth of defect (caverns and cracks); W_{PL} is the energy of plastic deformation per unit of surface.

RESULTS AND DISCUSSION

Consider an example of corrosion current modeling in defects on a metal surface of an underground pipeline near the OPS, taking into account seasonal temperature changes.

Near the OPS on the outer surface of the pipe metal there are defects such as caverns, pits, cracks. Under the influence of temperature, wet soil and internal pressure, defect sizes increase. The size of the defects and the nature of their spread can be controlled by devices and means of non-destructive testing [7]. Such control is needed as damage is more frequent near OPS, leading to 2.8 accidents per 1 km [8].

During operation, the pipeline is hot during operation near the NPC, and at some distance from the NPC there are areas prone to temperature fluctuations [8].. In those places there are caverns whose dimensions increase over time under the influence of seasonal temperatures in the range T = 313… 333 K. It is important that in this situation it is necessary to take into account corrosion processes on the metal surface and the potential of cathodic protection U_K.

Anode (corrosive) currents on the surface of an underground pipeline metal in defects near the OPS can be detected and monitored by devices of the БВС and ВПП types [9, 12, 15].

For modeling, we use the results of measurements of currents near the OPS (Table 1), which are presented in [14, 16].

Table 1. Anode current density depending on temperature

Time *t,* years	Temperature *T*, K	Anode current density I_a , A/m^2
1	293	56,0
	313	60,3
	333	64,6
3	293	37,4
	313	40,2
	333	43,0

The data in table 1 corresponds to 17G1C steel. The change in the anode current in the two considered (Table 1) variants for t_1 = 1 year and for t_2= 3 years does not exceed 6 %. Here T_0 = 293 K – normal temperature. The maximum pipe temperatures near OPS correspond to winter T_1 = 313 K and summer - T_2 [14, 16].

If we combine (2), the method of calculating the mechanical parameters that characterize the boundary state of the loaded internal pipe pressure (1) and the approach of neural networks, we will get a new mathematical model. On the basis of this model of type (1), (2) it is possible to estimate the pipeline resource taking into account seasonal changes in temperature and the corresponding values of the anode (corrosion) current (Table 1).

When using a model of type (1), (2), there may be difficulties due to the fact that additional measurements are required to find parameter E_0. The difficulty of determining the parameter E_0 and the pipeline resource can be overcome by using the cathodic protection potential of the UK instead of the parameter E_0 and improving the relation (2) accordingly:

$$I_a = I_0(T)\cdot\left(\exp\left(DE^*(T)/a(T)\right)\right)\cdot\left(1+\beta_W(T)\cdot W_{PL}(T)\right), \qquad DE^*(T)=G/(RT). \qquad (3)$$

In this case $DE^* = U_K - E_a$ and it should be taken into account that the parameters of relation (3) will depend on the temperature *T*; *G* is the activation energy of the corrosion process; *R* is a universal gas steel. If we give $DE*$ as $DE^* = G/(RT)$, this relation will have the form of the Arrhenius equation in the same way as in [19] for pitting corrosion.

The metal of the pipeline is usually covered with protective dielectric insulation and sometimes with a metal film (passive protection) [14].

There must be sufficient adhesion between the coating (film) and the metal, i.e. adhesion [7]. The interfacial layer between the metal and the cover is characterized by 4 basic energy parameters: the energy of the adhesive bonds γ_{ad} and its change $\Delta\gamma_{ad}$; change of interfacial tension $\Delta\sigma_m$; change interfacial energy $\Delta\gamma_m$; change ΔA_{ad} adhesion [18, 19].

On the above parameters, we formulate the limitations that follow from the article [18]:

$$\Delta\sigma_m \le \Delta\sigma_{m*}, \quad \Delta\gamma_m \le \Delta\gamma_{m*}, \quad \Delta A_{ad} \le \Delta A_{ad*}, \quad \Delta\gamma_{vad} \le \Delta\gamma_{ad*}, \quad \Delta W_{PL} \le \Delta W_{PL*}. \qquad (4)$$

where $\Delta\sigma_{m*}$, $\Delta\gamma_{m*}$, ΔA_{ad*} , $\Delta\gamma_{ad*}$, ΔW_{PL*} are empirical constants. Here, the restriction on the W_{PL} energy parameter is written similarly to the previous 4 parameters.

Relatios (1), (4) represent the strength criterion for a metal pipeline with a dielectric coating. The parameters of expression (1) are determined on the basis of the experiment, and the parameters of relations (4) will be determined on the basis of a computational experiment.

For specific calculations, you can use the information table 1, the initial geometric and physical conditions for the metal of the pipeline and structure, as well as the approach of neural networks [9-11]. Based on the data of the table 1, shows a test example for pipeline resource evaluation. To implement this example, a mathematical model of type (1), (3), (4) was used, taking into account $DE^*(T) = U_K - E_a$ and a computational experiment based on neural networks.

During the implementation of the test example, a database was created, to which the initial anode current density and potential values were submitted. Current and potential are presented in the form of two classes: class 1 (data for a pipeline that has no defects "defect-free pipeline"); class 2 (data for a pipeline that has a faulty "defective pipeline").

The example is implemented as Python programming modules using framework «Tensorflow» (computer software library). The structure of the neural network architecture is a root section that specializes in setting blocks (in this case we specify the corresponding two classes).

The neural network trains by modifying the weights with gradient algorithms based on the back propagation of the error with different parameters of the learning transfer process. This takes into account: the size of the batch normalization used, which accelerates the convergence of the algorithm; the number of eras; the number of iterations of the algorithm program; speed of training; decay factor and decay function that regulates the gradient optimization process in order to improve classification accuracy. After calculations at the output of the neural network, we obtain tabular data, which is predicted by this network (in our version, the finite values of currents and potentials, as well as the predicted value of time, that is, the pipeline resource, which meets the complex criterion of strength (1), (4).

The following partial data correspond to the test example for a 17G1C steel underground pipeline:

$$T_0 = 333\text{ K},\ D = 710\text{ mm};\ d=16\text{ mm};\ I_{a0} = 64{,}6\text{ A/m}^2;\ I_{az} = 12{,}9\text{ A/m}^2;$$

$$U_K=1{,}05\text{ V};\ \sigma_T = 350\text{ MPa};\quad H=h+c+r = 8{,}3\text{ mm};\quad t_* = 0{,}32\text{ year}. \qquad (5)$$

Here T_0, I_{a0} are the initial values of the anode current temperature and density, respectively; $t_*= 0{,}32$ year - pipeline resource; H - limit depth of defect; I_{az} is the ultimate value of the anode current density. In this case, the pipeline resource t_* corresponds to the final result of the noted test example, ie the maximum depth of defect H. The maximum depth of defect H is determined on the basis of the criterion of strength (1), (4).

On the basis of the computational experiment it is established that the new model ((1), (3), (4)) with an accuracy of 9… 11% allows to adequately predict the resource of underground pipeline.

CONCLUSIONS

1. The anode current density in a cavern on the outer surface of the oil pipeline near the oil pumping station (OPS) for 1 and 3 years is estimated. It is established that in the temperature range $T = 313\ldots 333$ K the change of the anode current density for the pipeline metal is about 6%.

2. Improved Kaesche type relation for anode current density in defect on the surface of the underground pipeline, taking into account the expression $DE^*(T) = U_K - E_a$., in which the U_K - cathodic protection potential is used as a basic parameter.

3. The basic relations and peculiarities of functioning of the new mathematical model ((1), (3), (4)) are formulated for the analysis of the influence of seasonal changes of temperature on corrosion processes that can lead to stress-corrosion cracking (SCC) of steel pipe metal near OPS.

In particular, the new model is based on an improved Kaesche type ratio for the anode current density, a new criterion for the strength of metal (1), (4), a method for estimating the limit state of a steel pipe loaded with internal pressure, and an optimization approach for the calculation of interconnected parameters using interconnected parameters and networks.

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