Сформовано новий критерій міцності та множину інформативних параметрів для моделювання напружено-деформованого стану (НДС) підземного металевого трубопроводу (ПМТ) з урахуванням системи дефектів типу каверна, у вершині якої знаходиться тріщина.

Проведено обстеження поверхні труб із конструкційної вуглецевої сталі 20, на які діє внутрішній гідростатичний тиск. Запропоновано для критерію міцності металу труби, який контактує з ґрунтовим електролітом, враховувати стадії пружної та пластичної деформацій.

Критерій міцності доповнено співвідношеннями для корозійного струму (типу Kaesche) і внутрішнього тиску, який діє на циліндричну трубу, з урахуванням непружної енергетичної характеристики поверхневого шару.

Для трубопроводу в нейтральному ґрунтовому середовищі проведені вимірювання поляризаційних потенціалів і корозійних струмів апаратурою ВПП (вимірником поляризаційного потенціалу) і БВС (безконтактним вимірником струму). Результати вимірюють відповідні дефекти типу каверн (піттингів), які утворилися на зовнішній поверхні підземного трубопроводу.

Для п'яти варіантів внутрішнього тиску p_i=5,5÷7,5 МПа приладами БВС та ВПП визначено струми та напруги для характерних поверхневих дефектів і на їх основі оцінено ефективний час досягнення тріщиною критичної глибини (ресурс труби), а також параметр надійності (характеристику безпеки) β.

Зі співставлення результатів експериментальних досліджень і відповідних розрахунків установлено, що відносні зміни швидкості корозії V_{cor} у 2,8 рази і, відповідно, параметра ресурсу ПМТ t_R в 3,1 рази більші, а параметра надійності β у 6,9 разів менші, ніж відносні зміни внутрішнього тиску p_T.

На основі аналізу параметра t_R, який характеризує ресурс ПМТ, встановлено, що ця залежність t_R від внутрішнього тиску p_T нелінійна і прямує до насичення.

Відзначена інформація є важливою для удосконалення методів контролю ПМТ нафтогазових підприємств, зокрема, методик коректного оцінювання густини анодного струму у дефектах металу на зовнішній поверхні підземного трубопроводу з урахуванням зміни внутрішнього гідростатичного тиску

Ключові слова: підземні трубопроводи, нафтогазові підприємства, механічні напруження, гідростатичний тиск, корозійні струми, розкриття тріщини

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IMPROVEMENT OF THE TOOLSET FOR DIAGNOSING UNDERGROUND PIPELINES OF OIL AND GAS ENTERPRISES CONSIDERING CHANGES IN INTERNAL WORKING PRESSURE

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1. Introduction

Forecasting of strength and durability of underground metal pipelines (UMP) at oil and gas enterprises should be carried out in order to estimate residual levels of reliability and resource by using optimization methods. Important processes in this aspect are related to mechanical loads and soil corrosion. More to the point, mechanical strains in a pipe intensify corrosion processes at the interface "metal surface–soil electrolyte". A double electric layer (DEL) is formed at the boundary between the two specified environments. Metal ions under the influence of mechanical stresses pass through a DEL and form corrosive streams. Since the outer surface of a pipe's metal is heterogeneous, then the corrosive surface currents would also be heterogeneous. This leads to that corrosion cavities (pitting) of different depths can form at the outer surface of the pipe.

Recent years have seen the development of methods for diagnosing surface corrosion defects in UMP based on digital image processing [1]. Corrosion processes refer to the general and local corrosion. General corrosion occurs over the entire or any part of the UMP surface at a rate of 0.1–0.5 mm/year [2]. The result of general corrosion is the complete dissolution of a metal's surface or some part of its surface [2]. During this process, the depth of corrosion penetration in some areas may be somewhat larger than in others [2]. Much more often, the surface of a pipe is exposed to a local corrosion, whose characteristic feature is the high speed of metal's destruction in certain areas, reaching 1–10 mm/year [2]. The result of local corrosion is the destruction of metal into depth, while at the same time the neighboring sections of a pipe can demonstrate minimal corrosion. Corrosion rate is determined based on the depth of the formed damage, which is estimated instrumentally [2].

The characteristic variations of local corrosion are pitting, contact, and corrosion in spots [2]:

1. The rate of pitting corrosion is 3–10 mm/year. Pitting corrosion is characterized by the formation of cavities that originate at the surface and take the form of cavities. In some cases, the development of pits is accompanied by the destruction of a pipe's wall. The shape of pits can take different sizes, particularly small, medium size, narrow, wide, deep, etc.

2. Contact corrosion is a process that occurs between two metals that differ in their electrochemical characteristics. The result of the process may be local corrosion damage in the form of pits, located in a chain, or pits that merge into a single common pit.

3. Corrosion in spots is characterized by the formation of damages at the surface of a metal in the form of separate spots whose area significantly exceeds the depth of corrosion penetration. The depth of damage in this case is usually 0.5–1.0 mm, so this type of corrosion is less dangerous than other variants of local corrosion.

Development of new techniques for nondestructive testing of underground pipelines is a relevant strategy at present, as it could reduce the cost of experimental research in order to confirm the conditions for extending the terms of operation of UMP at oil and gas enterprises.

In this regard, a coated pipeline in a soil environment should be considered as a two-layer pipe with an external defect of the surface pit type.

We shall consider a pipe to be cylindrical; a pit shall be modeled as a half of the ellipsoid elongated in the direction perpendicular to the pipe's surface. To forecast the resource of an underground pipeline made of steel, we shall use variants of criteria from the fracture mechanics and qualimetry, taking into consideration the optimization approach.

2. Literature review and problem statement

It is known that external and internal defects affect the reliability (strength, durability) of UMPs at oil and gas enterprises [3, 4].

It was established that the issue of quality of underground metal pipelines (UMP) is associated with processes at the interface "metal–soil environment" [5].

The models of damage in metals, reported in the scientific literature, are compared based on the depth of corrosion, choosing different influential parameters to model similar classes of corrosion according to requirements by standards [6]. Papers [3–6] do not account for the features of mechanical loading (internal hydrostatic pressure, soil pressure, etc.), and do not consider informational streams for defect detection.

Study [7] accounted for the possibility of using a magnetic flux (magnetic flux) to diagnose defects in a pipe's metal. The authors also considered the size effect of the Young modulus [7, 8]. However, the cited approach [7, 8] does not account for the possibility of remote non-destructive approach to measuring defect parameters, as reflected in scientific work [9].

Currently, diagnosing the metal of pipes (UMP) at oil and gas enterprises implies the use of a method of contactless measurements of currents and potentials [9]. This makes it possible to control the character and conditions of defect behavior [10, 11].

It is appropriate to model the physical-chemical processes in pipelines (UMP at oil and gas enterprises) taking into consideration the parameters of the stressed-strained state (SSS) and energy characteristics of interphase layers based on ratios reported in studies [12, 13].

However, papers [12, 13] do not describe the connection between SSS parameters and electrical currents and potentials for metals used in UMP. The connection between the SSS parameters and electric currents and metals' potentials is partially described in works [14, 15], based on the results from performed studies. The parameters of SSS are associated with an important parameter from the fracture mechanics of materials – a stress concentration factor (SCF).

Paper [16] gives information on the SCF for corrosion pits. The connection between the energy characteristics of interphase layers and a metal's SCF is partially presented in [17, 18]. However, the cited papers [16–18] do not provide information about pits and characteristics of interphase layers with respect to electrical currents and potentials.

Take into consideration that a pipe (in UMP at oil and gas enterprises) is exposed, perpendicular to a crack, to annular stresses, and then the crack opening is determined from a formula that takes into consideration the -model of crack opening and a stress intensity factor [19]. They also partly account for the geometry of a defect (a crack) [20, 21]. Taking into consideration the internal pressure, it is advisable to use a crack opening expression for elastic and plastic deformation [22].

It should be noted that the above techniques make it possible to comprehensively specify the procedure for calculating the mechanical parameters of a pipe with defects and, consequently, to improve the qualimetric approach to the quality issue related to UMP at oil and gas enterprises, which is partially presented in publications from Canada [23, 24]. In addition, the quality criterion for UMP is partially represented in papers [9, 10]. However, the cited studies [9, 10, 23, 24] do not consider the effect exerted on the quality of UMP by mechanical stresses and parameters that characterize defects. Positive in this aspect is the fact that papers [9, 10] report initial data and informational support, as well as a toolset, for improving the criteria of quality and investment projects at enterprises [25, 26].

Issues on diagnosing the oil and gas enterprises' UMPs in a corrosion-resistant environment taking into consideration pressure are relevant as the underground pipes are exposed to mechanical loads from gas, oil, and soil. It is also worth considering the comprehensive effect of hydrocarbons flows, soil environment, and compressor stations, which is accompanied by a corrosion fatigue of metal (steel).

3. The aim and objectives of the study

The aim of this research is to improve the toolset related to calculating the levels of resource and reliability of underground metal pipelines (UMP) at oil and gas enterprises taking into consideration the influence of internal pressure on the stressed-strained state parameters (SSS).

To accomplish the aim, the following tasks have been set:

– to inspect the surfaces of pipes made from structural steel using a polarization potential meter and a contactless current meter and to compile a database of informational parameters to process the results from experiment;

– to improve the criterion of strength for UMP with a system of surface defects (cavities extending into cracks);

– to device a mechanism for assessing the parameter of a pipe's metal resource and the reliability level of oil and gas enterprises' UMPs.

4. Assessing the strength and reliability of an underground metal pipeline with a defect

It is advisable to treat a coated pipeline in a solid environment as a two-layer pipe with an external defect of the surface pit type.

We examined a metallic pipe MP made from the structural carbon steel 20.

We believe that the metal of a pipeline (MP) with a system of surface defects (pits). is exposed to internal hydrostatic pressure in the range of up to 7.5 MPa.

A pipe is located underground at a depth of 0.8...1.0 m. Let the outer diameter of the pipe be D, wall thickness d, inner diameter $D-d$ [5].

We consider the pipe to be cylindrical; a pit is modeled as a half of the ellipsoid elongated in the direction perpendicular to the pipe's surface. To forecast the resource of an underground pipeline made of steel, we use variants of criteria from the fracture mechanics and qualimetry, taking into consideration the optimization approach.

Under the influence of soil moisture, at the outer surface of the pipe there form corrosive defects of the cavity type, cracks, pits, which extend to the depth of the metal [5].

Since the pipe is exposed to, perpendicular to a pit (crack), annular stresses σ_θ, the crack opening δ_t takes the form [12, 19]:

$$\delta_t = \frac{8\cdot\sigma_Y\cdot a_t}{\pi\cdot E}\times\ln\sec\left(\frac{\pi}{2}\cdot\frac{M_T\cdot\sigma_\theta}{\sigma_Y}\right),$$

$$M_T = K_{sh}/K_{pl} = \left(1+\beta_T\cdot\lambda_T\right)^{0,5},\quad \lambda_T = a_T\cdot\left(Dd/2\right)^{0,5}, \qquad (1)$$

where a_t is the crack length; σ_Y is the yield limit; E is the elasticity module of a pipe's material; K_{sh} and K_{pl} are the stress intensity factors in the sphere and plate; β_T=0.62 is the material constant (β_T=1.25 if $\lambda_T\leq 5$).

Take into consideration a metal strengthening coefficient m and the depth of a cavity with a crack $b=h+c$. Since the deformation of a metal $\varepsilon_Y=\sigma_Y/E$, then for $\varepsilon/\varepsilon_Y\leq 1$ – $\varepsilon=\sigma/E$. If $\varepsilon/\varepsilon_Y>1$, then $\varepsilon=(\sigma/\sigma*)^{1/m}$, $\sigma^*=\sigma_Y/\varepsilon_Y^m$. In this case [22]:

$$\delta_{te} = \frac{\pi\left(M_T\cdot\sigma_r\right)^2\cdot b}{2\cdot E\cdot\sigma_Y},$$

$$\delta_{tp} = \frac{\pi\sigma_Y\cdot b}{8\cdot E}\left(9\cdot\left(\frac{M_T\cdot\sigma_r}{\sigma*}\right)^{1/m}\cdot\frac{E}{\sigma_Y}-5\right). \qquad (2)$$

Here, δ_{te}, δ_{tp} is the crack opening for the case of elastic and plastic deformation.

The parameter of crack opening δ_{1C} is related to the coefficient of stress intensity (SIC) K_{1SCC} and overvoltage ζ of the reaction (deviation of electrode potential from its equilibrium thermodynamic value in the polarization of an electrode under current) of dissolving a metal via known ratios [18]:

$$K_{1SCC} = \sqrt{\frac{E}{1-\nu^2}\cdot\left(WPL - z_{si}F\rho\delta\frac{\zeta}{M}\right)},$$

$$K_{1SCC} = \sqrt{E\cdot\sigma_T\cdot\delta_{1C}}, \qquad (3)$$

where z_{si} is the formal charge of solvated ions; F – is the Faraday constant; δ is the width of a propagating microcrack's front, m; M is the molecular weight of a metal, g/mol; K_{1SCC} is the threshold value of SIC, that is, the minimum value corresponding to the beginning of a corrosion crack propagation; WPL is the specific energy spent on plastic deformation of the near-surface layer of a body during the formation of a new (juvenile) surface in it; v is the Poisson coefficient of a metal.

Based on a computational experiment for different grades of steel it was determined that 3 variants of the parameter $\delta_{1C}(\delta_{te}, \delta_{tp}, \delta_{tp})$ exert an insignificant influence on the numeric value of SIC K_{1SCC} (corresponding maximum difference, that is an error does not exceed 10 %).

A WPL parameter is included in the known relationship (strength criterion) by Griffith– Irwin–Orowan [18]:

$$\sigma_* = \sqrt{\frac{4E\cdot WPL}{\pi\cdot L_T\left(1-v^2\right)}},\quad \sigma_* = \sqrt{\frac{4E\cdot WPL}{\pi\cdot L_T}}, \qquad (4)$$

where $L_T=a_t$ is the crack length.

Here, in (4), the first formula is recorded for a flat deformation, the second – for a flat stressed state; σ_* is the critical stress (tensile strength); $WPL=J/2$; J is the Rice's integral, which has an energy content.

Based on the results of research into a contact deformation of different grades of steel, we have established an empirical relation that links SIC K_{1SCC} to WPL [18]:

$$K_{1SCC} = a_1\cdot\sqrt{WPL} - a_2;$$

$$a_1 = 2{,}26\cdot 10^8\frac{\sqrt{\text{H}}}{\text{m}};$$

$$a_2 = 6{,}98\,\text{MPa}\cdot\sqrt{\text{m}}. \qquad (5)$$

Ratios (3) to (5) form in a combination a new variant of the strength criterion for a pipeline's metal. The parameters for expression (4) are determined based on the experiment with deformed metal (steel) samples, and the parameters for ratios (3), (5) are assessed based on the computational experiment.

Assume that an empirical correlation holds between crack opening δ_{1C} and geometric parameter δ, which characterizes width of the juvenile surface of a crack [18]:

$$\delta_{1C}=\xi_\delta \times \delta, \tag{6}$$

the corresponding value for empirical constant $\xi_\delta=1$.

Criterion (3) to (5) will be supplemented with ratios for corrosion current I_a (the Kaesche type) and internal pressure p_{cr}, which acts on a cylindrical pipe, taking into consideration the energy characteristic of a surface layer [18]:

$$I_a = I_{as}\cdot\left(1+\beta_W\cdot WPL\right)= \\ =\frac{\alpha\cdot\chi\cdot\Delta\psi_{ak}}{\delta\cdot\ln(c/\delta)}\cdot\left(1+\beta_W\cdot WPL\right), \tag{7}$$

$$p_{cr}=\frac{2\sqrt{2}\cdot d\cdot\sigma_T}{3K_t\cdot D}\cdot\frac{(1.5+K_z)\cdot(r_0+c)^4}{(r_0+c)^4+0.5\cdot r_0^2(r_0+c)^2+r_0^4}, \tag{8}$$

where

$$K_z=\frac{\left(\dfrac{d_1-c}{2}\cdot\dfrac{2(d_1-c)+3r_0}{d_1-c+r_0}-\dfrac{3d}{2K_t}\right)}{\left(\dfrac{d}{K_t}+\dfrac{r_0}{3}\cdot\left(\dfrac{r_0^3}{(d_1-c+r_0)^3}-1\right)\right)};$$

$$\beta=\frac{r_0}{d_1-c};$$

α is the angle at the top of a crack; χ is the electrical conductivity of electrolyte; $\Delta\psi_{ak}$ is the Ohmic change in potential between the anode and cathode parts (anode – apex, cathode – shores of a crack); c is the crack depth; $h+c+r$ is the total depth of a defect (cavity and crack, the crack is on the continuing cavity (pit)); h is the cavity depth; r is the radius of curvature at the top of a crack.

Ratios (1) to (8) and quality criterion [5] will be used to assess the SSS parameters and the crack propagation conditions for a pipeline in a soil neutral medium (hydrogen pH≈7).

5. Quality criteria for the metal of an underground pipeline at oil and gas enterprises

Consider the product of type $k_P=k_1\times k_2\times k_3$ similarly to paper [5]:

k_1 – coefficient of the level of reliability of oil and gas enterprises' UMPs;

k_2 – coefficient that characterizes the level of UMP metal's strength σ_*;

$k_3=k_3(T_S, N_C)$ – coefficient that characterizes the time of trouble-free operation T_S (resource) of a structure (a pipe) taking into consideration N_C (N_C – the number of load cycles, that is the test base on a corrosion resistance fatigue).

Similarly to paper [5], a qualimetric quality criterion for a section of the oil and gas enterprises' UMP will be represented in the form:

$$Z_1=\beta_1 k_1\cdot k_2\cdot k_3+\beta_2\prod_{i=4}^{9}k_i, \tag{9}$$

where $k_4(D_f)$, $k_5(n_Z, \Delta K_{th})$, $k_6(\sigma_{ve}, N_C)$, $k_7(K_S)$, $k_8(U_P)$, $k_9((h+c)/d)$ are the coefficients that characterize defect amount D_f, strengthening n_Z, limit of corrosion fatigue $\sigma_{ve}(N_C)$, the influence of a coating on corrosion resistance K_S, compliance with the optimal range of polarization potential U_P; relative depth of a cavity and a crack of maximum dimensions; β_j (j=1, 2) are the weight coefficients, which are defined by an expert method; K_{th} is the threshold value of SIC K_1 under the influence of a mechanical load; ΔK_{th} is the spread of K_{th} over a load cycle; d is the pipe thickness; h, c are the depth of a cavity and a crack, respectively.

Here, formula (9), in contrast to paper [5], takes into consideration the relative depth of a surface defect $k_9((h+c)/d)$.

6. Results of forecasting the resource and reliability of an underground pipeline at oil and gas enterprises accounting for changes in internal working pressure

We measured the currents and potentials of a pipeline in a neutral environment using the CCM (contactless current meter) and PPM (polarization potential meter) equipment in line with procedures from articles [5, 27]. Based on appropriate measurements, we have found defects of the cavity type (pits), which formed at the outer surface of the underground pipeline; the assessment of corrosion currents has been performed as well.

Our experimental study involved pipes made from structural steel 20, provided that the protective potential at the UMP surface was less than the boundary potential $\varphi_{P*}=-0.85$ V [5]. Accordingly, the anodic dissolution of steel at the surface of the pipe occurs in cavities (pits), for which a condition of corrosion (cathodic) protection $|\varphi_{P*}|>0.85$ V is not satisfied [5]. Cracks of depth c can form in the prolongation of cavities.

We have experimentally determined a hydrogen indicator pH≈7.0 for soil (external corrosive environment outside the pipe) in line with procedures from articles [5, 27]. In addition, we assessed the reliability of pH control in line with a procedure from papers [28, 29] and determined that reliability of the pH estimate exceeds 90 %.

The initial data (parameters) for the pipe and metal (structural steel 20) are similar to those in paper [18]:

$$p=5{,}5\div7{,}5\ \text{MPa};\ \Delta p=0{,}5\ \text{MPa};$$

$$h=4\ \text{mm};\ d=10\ \text{mm},\ d_1=6\ \text{mm},$$

$$D=2R=0{,}76\ \text{m},\ \sigma_*=245\ \text{MPa};$$

$$\sigma_B=410\ \text{MPa};\ p_{cr*}=9{,}3\ \text{MPa}, \tag{10}$$

where D is the pipe diameter; $d_1=d-h$; σ_T, σ_* is the yield and strength limits; p_{cr*} is the critical (maximum) internal pressure in a pipe.

For each variant of internal pressure p_i=5.5÷7.5 MPa we use the CCM and PPM devices to determine the currents and voltages for the characteristic surface defects; based on them, we estimate the time it takes for a crack to reach critical depth (a pipe resource), as well as the reliability parameter β considering data from papers [5, 18, 27, 30] (for five variants of the initial corrosion rate). The results from measurements and calculations are given in Table 1. It was taken into consideration that with an increase in the length of a crack c the anodic (corrosive) current i_a decreases and such a dependence $i_a=f(c)$ is nonlinear [18]. It is also advisable to take into consideration that for the plastically deformed region of a metal at the top of a crack (for a juvenile surface) the intensity of corrosion (corrosive current) grows by about 9÷12 % compared to the elastically deformed region.

Based on the ratio for anodic current (the Kaesche type) (7) in the defect at the surface of the deformed metal and appropriate experimental data obtained for the samples of steel 20 using the CCM and PPM equipment, it was found that for the plastically deformed region of a metal the intensity of corrosion (corrosive current) is higher by about 10 % compared to the elastically deformed region. This type of information was not taken into consideration earlier for the assessment of a pipe resource (for a metal of the underground pipeline) and this phenomenon has been accounted for in a given paper.

Here, the reliability parameter β (a safety characteristic) based on a probabilistic approach is determined from ratios [28–30]:

$$\beta = Y_{RM} / Y_{SRM}, \tag{11}$$

where Y_{RM} is the strength reserve; Y_{SRM} is the standard of reserve strength.

Results from experimental data were obtained for an underground gas pipe made from structural steel 20 (initial data the type of (10)) in a soil electrolyte based on the CCM and PPM equipment, taking into consideration a quality criterion (9); they are given in Table 1.

Table 1

Resource of an underground pipeline at oil and gas enterprises

No. of entry	Pressure in pipe p_T, MPa	Initial values of corrosion rate, V_{cor}, mm/year	Time it takes for a crack to reach critical depth 0.7d (resource) t_R, years	Parameter (level) of reliability β
1	5.5	0.41	8.53	5.66
2	6.0	0.73	4.09	5.59
3	6.5	1.05	2.46	5.53
4	7.0	1.32	2.02	5.48
5	7.5	1.63	1.47	5.44

Based on data from Table 1, we obtain relative changes in parameters:

$$w_p = \frac{p_{T\max} - p_{T\min}}{p_{T\max}} = 0.27;$$

$$w_V = \frac{V_{cor\_\max} - V_{cor\_\min}}{V_{cor\_\max}} = 0.75;$$

$$w_V = \frac{w_V}{w_p} = 2.8;$$

$$w_t = \frac{t_{R\max} - t_{R\min}}{t_{R\max}} = 0.835;$$

$$w_V = \frac{w_t}{w_p} = 3.1;$$

$$w_\beta = \frac{\beta_{\max} - \beta_{\min}}{\beta_{\max}} = 0.039;$$

$$w_V = \frac{w_p}{w_\beta} = 6.9. \tag{12}$$

Comparison of results from calculations (12) shows that the relative changes in the rate of corrosion V_{cor} are 2.8 times and, accordingly, the parameter of UMP resource t_R are 3.1 times, larger, and the parameter of reliability β is 6.9 times less, than the relative changes in internal pressure p_T.

7. Discussion of results of control over the underground pipelines of oil and gas enterprises in soil environments with the consideration of changes in internal working pressure

The considered example (Table 1) confirms the possibility and usefulness of modeling, using ratios (1) to (10), of the deformation and corrosion processes in underground pipelines at oil and gas enterprises.

A specific example has been considered; the result of its analysis, taking into consideration a change in the intensity of anodic dissolution in the defects of coating an UMP for a particular pipe (made from steel 20) with corrosive defects at the outer surface, is the pH estimation of the soil electrolyte. The assigned initial conditions (10) were accounted for.

Based on analysis of the parameter t_R, which characterizes the UMP resource, it was determined that the dependence $t_R=f(p_T)$ is nonlinear (Table 1). Relative changes in parameters from Table 1 regarding $w_t / w_V = 1{,}11$ are partly related to nonlinearity of the corrosive process, as well as to different speeds of anodic dissolution of a metal (steel) in the elastic and plastic ranges of crack propagation.

Based on the calculations, it was established that for the range of pressure change P=5.5÷7.5 MPa a relative change in the resource parameter t_R at the beginning of the range is 1.76 times greater than that for the end of the range. Consequently, it can be argued that the increase in pressure p_T leads to that the resource parameter t_R tends to saturation.

The unbending Rehbinder effect in the current study concerns the cracks and is manifested by reducing the strength characteristics of a pipe's metal. Quantitatively, the relevant information may be obtained by evaluating the energy characteristic WPL (3) to (5), (7) during the consideration and determining this parameter in the vicinity of the crack apex. The procedure for assessing changes in WPL parameter during the deformation and corrosion processes is given in paper [18].

The results of the current work were obtained from our experimental research using the CCM and PPM equipment. In addition, in this paper we used the approaches and methods of mathematical modeling to describe physical processes in metallic solids with surface defects of the cavity, pit, crack types. Specifically, attention was paid to the deformation and corrosion processes. The main theoretical approaches concerned the thermodynamics of nonequilibrium processes, the mechanics of deformed solids, the mechanics of destruction, the theory of a mixture of continuous media, the physics and mechanics of composite materials.

The limitations of this study relate to the material and dimensions of pipes, as well as the environment and conditions of mechanical loading. In particular:

– internal pressure constraint – p≤7.6 MPa;

– maximum pipe diameter – D≤1,420 mm, minimum – 15 mm;

– maximum pipe thickness – 32 mm, minimum – 2.8 mm;

The most popular pipe sizes (in mm) are 1,420, 1,220, 1,020, 920, 820, 720, 530, 426, 377, 325, 273, 219, 159, popular thickness of pipes (in mm) are 7, 8, 9, and 10 mm. For a pipe with a cross section of 1,020 mm, the most common thicknesses are 10, 11, 12, as well as 14 mm.

Constraints on the potential of a cathodic protection system (CPS) are as follows. It was experimentally established and theoretically confirmed that at potentials below −1.1 V it is possible to accelerate steel destruction due to excessive increase in pH of a near-electrode layer under condition of high temperatures, which promote the development of corrosion cracking. The maximum value of CPS potential is −0.85 V.

Further directions of this study worth considering are: accounting for seasonal changes in temperature, environmental aspects, taking different types of soils into account.

8. Conclusions

1. We have studied defects (the type of cavities with cracks at the top) at the interface metal–electrolyte for pipes made from steel 20, placed in a neutral soil environment, by using non-destructive testing devices, a polarization potential meter (PPM) and a contactless measuring meter (CCM), to control the potentials and corrosion currents. Based on the results of our experimental study, the database is formed underlying which is information about internal pressures of gas inside a pipe and the values of corrosive currents. The relevant data are interpreted as the base of initial conditions for estimating the character of corrosion dissolution of metal in the defects of a coating at the border with a corrosive medium.

2. A new strength criterion has been proposed for a metallic pipeline, taking into consideration a coefficient of stress intensity K_{1SCC}, overvoltage ζ of the reaction of anodic dissolution of the metal, as well as the energy characteristic of a surface layer WPL.

3. It was established by using the results from our experimental research into loading a gas pipe with internal pressure, a new criterion of strength, as well as information on a change in the character of anodic dissolution associated with the plastic deformation of the juvenile surface at the top of a crack, that the change in the internal hydrostatic pressure in a pipe from an underground metal pipeline in the range of 27 % is accompanied by a decrease in the parameter of the metal pipe resource by 83 %, and the corresponding probability parameter of reliability , which characterizes patterns in the propagation of corrosive defects at the outer surface of a pipeline's metal, decreases at the same time by about 4 %.

Based on the obtained results and related procedures [5, 18, 27, 31], it is possible to assess the influence of internal pressure p_T on the resource and reliability of UMP in acidic, alkaline, and neutral soil environments.

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