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Diagnostics of Temperature Regime of Technological Environments of Underground Pipelines in the Monitoring System of Oil and Gas Enterprises for Providing of Safe Exploitation

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Abstract: The diagnosed density of corrosion was diagnosed on the outer surface of the underground metal pipeline, depending on the distance L to the compressor station, taking into account the influence of soil, defects, thermal impulses, mechanical vibrational vibrations and corrosion fatigue.

The basic relations of the mathematical model for the description of thermal processes and mechanical vibrational vibrations that lead to low-cycle corrosion fatigue in the pipe are proposed.

It is noted that the measurement of corrosion currents and polarization potentials at the boundary of the metal pipeline–soil can be detected by devices of types BVS (noncontact current meter), VPP-M (polarization potential meter) and equipment for for diagnostic inspections and monitoring of corrosion protection of underground pipelines (UGPL).

Consider for compare the distribution of corrosion current densities and accidents for the pipeline at a distance of L=0..30 km from the compressor station. It is found that the correlation coefficient between them $K_{LD}=0,76$ is not enough to establish causation. A difference is formed in which the corresponding corrosion current density distribution for a non-oscillating temperature background is subtracted from the total corrosion current density distribution in the range L=0…30 km. In this case, the part of the distribution that is related to the frequency of thermal pulses is highlighted.The correlation coefficient of $K_{WD}\approx 0.92$ is established between the part of the distribution that is related to the frequency of thermal pulses and the distribution of accidents for the pipeline at a distance of L=0…30 km from the compressor station. Based on K_{WD}, it can be argued that the causal relationship between the distribution of heat pulses and accidents is quite plausible.

The noted information is important for improving the methods of operation of compressor stations of oil and gas enterprises, taking into account changes in the frequency of heat pulses with regard to improving the quality of by-laws on labor protection regarding gas supply systems.

Keywords: underground pipeline, oil and gas enterprises, thermal impulses, thermal background, corrosion current.

I. INTRODUCTION

The most important components of Ukraine gas transportation system are gas, pipeline metal (the main element of the linear part), soil and the air environment. They interact with each other in different temperature, sometimes unsteady conditions.

Gas pipelines and compressor stations (CS) provide continuous gas transit. In this case, they may deviate operating conditions and violations of the respective thermal modes. This is especially true for large-diameter underground metal pipelines (UMP) that are in different climates.

The instability of technological regimes is accompanied by corrosion processes under operating conditions and stress corrosion cracking (SCC) under stress, which affects the performance of underground metal pipelines (UMP) and determines the prospects of their functionality. The pipeline, which lies in the soil, during transportation on it substances with a temperature different from the soil temperature, is a source of heat and creates a temperature anomaly on the soil surface, which is recorded by special devices (thermal imagers, pyrometers, thermometers bimetallic).

The competitiveness of the oil and gas (gas transportation) enterprises is ensured by the reliable operation of the compressor stations and the corresponding efficient gas supply. The efficiency of the pipeline systems depends on the thermal modes of the compressor station (CS).

A large number of accidents correspond to sections of the gas pipeline (20–30 km after compressor stations). These areas are susceptible to corrosion due to the effect of temperature and humidity on the pipe metal in places where the insulation is damaged.

Solving the problems of technical and environmental safety at oil and gas facilities is an important area of research.

The relevant relevance is related to the control of corrosion processes on the surface of the metal pipe in places of damage to the insulation and the corresponding effects of temperature and humidity on these processes.
In this context, it is necessary to diagnose the heat transfer modes

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of underground metal pipelines (UMP) with the environment and to develop measures aimed at optimizing the thermal modes of cathode stations (CS) in order to stabilize corrosion processes and (SCC).

II. LITERATURE REVIEW AND PROBLEM STATEMENT

In [1, 2], the results of studies of control over the parameters of the technological environment of underground metal pipelines (UMP) are presented. The conditions of safe operation of UMP have been established. However, issues related to improving the quality criteria remained unresolved. The reason for this may be the objective difficulties associated with the lack of experimental data [3]. An alternative to overcoming such difficulties can be tools for improving investment projects [4, 5] of enterprises. This is the type of approach used in [6, 7]. However, soil moisture pipelines (UMP) analysis models should take into account soil moisture [8, 9], as well as its freezing [10] and freezing [11]. All this gives grounds to claim that it is advisable to carry out a study devoted to taking into account the effect of periodic changes in ambient temperature on underground metal pipelines (UMP) in the same way as in [12].

In [13, 14] proposed a technique for predicting thermal losses of underground pipelines. Appropriate assumptions of implementation of the methodology are established. But the issues related to the peculiarities of the thermal regimes of the compressor stations remained unresolved. This may be due to the difficulties associated with the imperfection of estimating the heat transfer coefficient from gas to soil, which depends on a large number of factors [15, 16]. Therefore, determining the actual heat transfer coefficient k_t is a rather complex and in many cases an unsolved problem [15, 16]. The method of calculating the heat transfer coefficient k_t is presented, in particular, in articles [16, 17], but this technique is mainly concerned with pipeline design modes. A variant of overcoming the corresponding difficulties within the problem of estimation of the coefficient of heat transfer from gas to soil is the development of tools for describing the interaction of media at the soil-pipe boundary [9].

Important in this context, given the information [1–41], is the procedure for determining the corrosion current density on the surface of an underground metal pipeline (UMP), since corrosion currents lead to crack growth and the fracture of pipe metal [2].

III. THE AIM AND OBJECTIVES OF THE STUDY

The aim of the study is to diagnose the corrosion current density on the surface of an underground metal pipeline, depending on the distance to the compressor station, taking into account the interaction of media at the soil-pipe interface. Important in this context is the identification of factors and diagnostics of temperature regime of technological environment that may disrupt the reliable operation of underground oil and gas pipelines.

The achievement of the stated goal involves the following tasks: 1) to carry out the diagnose corrosion current density in a metal pipeline depending on the distance to the compressor station; 2) to evaluate the corrosion current density depending on the number of thermal pulses at a distance $L = 0\ldots 30$ km. from the compressor station; 3) to compare the relative density of corrosion current with the density of accidents at a distance of $L = 0\ldots 30$ km from the compressor station on the basis of information about the corresponding distributions for the surface of underground pipelines.

IV. MATERIALS AND METHODS OF CORROSION CURRENT DENSITY DISTRIBUTION ON THE PIPELINE SURFACE

One of the most promising methods for monitoring the status of pipelines is thermal non-destructive control (TNC) [18]. Compared to other methods, (TNC) have a number of advantages, which include distance, security, high performance [18]. The pipeline (UMP), which lies in the soil, when transporting the substance with a temperature different from the temperature of the soil, is a source of heat. The underground metal pipeline (UMP) creates a temperature anomaly on the soil surface, which is recorded by special devices (thermal imagers, pyrometers, bimetallic tube thermometers) [18, 19]. As a result of the analysis of articles [2, 3] using artificial neural networks (ANN), it is proposed to analyze the information obtained as a result of diagnosing, which is done through devices of types BVS (noncontact current meter), VPP-M (polarization potential meter); and equipment for diagnostic inspections and monitoring of corrosion protection of underground pipelines – Fig. 1.

Fig. 1. Equipment for diagnostic inspections and monitoring of corrosion protection of underground pipelines (UGPL)*

Note:** *applicant and patent holder* ***Karpenko Physico-mechanical Institute of the NAS of Ukraine*, Ukraine; http://uapatents.com/*

Also, a technique for predicting the life of an underground metal pipeline (UMP) with a detected defect was developed, taking into account the values of soil (hydrogen index) in the vicinity of the pipe surface and the effect of corrosive fatigue of metal [3, 9].

Some thermal and hydraulic properties of the soil have been determined using experimental methods and predictive modeling in the same way as in [20].

V. RESEARCH RESULTS AND DISCUSSION

5.1. Results of diagnostics of temperature regime of technological environments of underground pipelines in the monitoring system of oil and gas enterprises

The often, the cause of damage to underground pipelines is their external corrosion, which occurs as a result of the contact of the metal pipes with the soil and the destruction of the protective layercoating [20].

The location of damage to the underground pipelines of oil and gas enterprises due to the violation of the waterproofing protective layer can be detected by devices of type BVS, VPP-M (Fig. 2) and equipment for for diagnostic inspections and monitoring of corrosion protection of underground pipelines (UGPL) [2, 3].

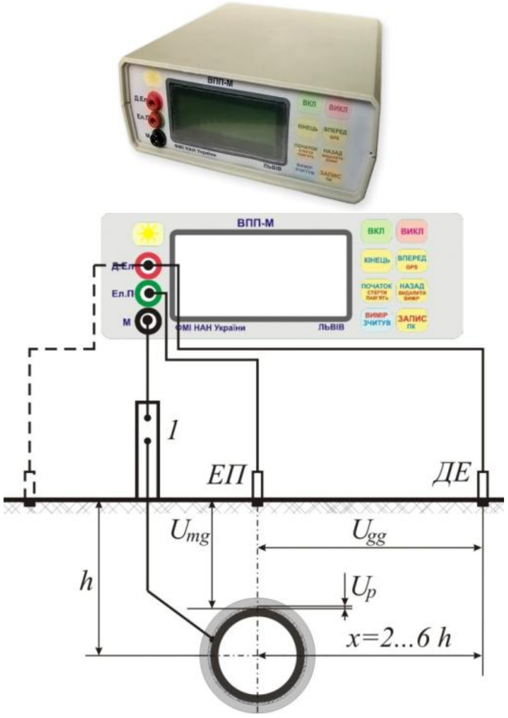

Fig. 2. Digital instrument (VPP-M*) and connection scheme for measuring constant and alternating electric voltages and determining the polarization potential

***Note:** Pat. 52293 Ukraine, IPC (2009) G 01 V 3/00, C 23 F 13/00. Device for determining the location and measurement of potential of underground pipelines / R. Dzhala, B. Verbenets; applicant and patent holder **Karpenko Physico-mechanical Institute of the NAS of Ukraine**, Ukraine. – No. u2010 00756; stated. 26.01.2010; Positive decision 08.06.2010; published Aug 25, 2010, Bul. No. 16.

In [20] it is noted that some sections of the pipeline are characterized by different parameters (and possibly with the presence of damage). As a result of diagnosis on the soil surface, we obtain similar temperature distributions. That is, the damage on the background of such distributions will not be detected, will be detected incorrectly or incorrectly identified.

It can also be assumed that the presence of local or distributed soil heterogeneities is often the cause of diagnosis errors [21]. In this case, a local or long-lasting change in the properties of the soil and its surface can cause a temperature difference, which will be identified as a defect [21]. Also, different sections of the soil have an influence on the results of temperature measurement, as each of them has the same environmental conditions across the accommodation zones, taking into account the real conditions of heat exchange at the boundary between the pipe and the soil [22].

The possibility of estimation of thermal losses of underground pipelines with the using of models and methods that take into account the change of conditions of heat exchange on the surface between the pipe and the external environment is shown [23].

The change in gas temperature *T(z)* along the pipeline (along the z axis) is given by the relation [16]:

$$T(z)=T_{GR}+(T_0-T_{GR})\times\exp(-a\times z)+D_S\times(1-\exp(-a\times z))/(aL). \quad (1)$$

Here $D_S=D_L\cdot(p_n-p_k)+q_L\cdot\Delta h/C_P$; T_0 is the gas temperature at the inlet of the pipeline; T_{GR} is the soil temperature; D_L is the coefficient Joule-Lenz; C_P is the heat capacity of gas at constant pressure; Δh is the height difference between the ends of the pipeline; p_n, p_k is the pressure values at the beginning and end of the pipeline; $a=k\pi D/(C_P\cdot M)$; k is the coefficient of heat transfer from pipeline to soil, L is the length of the pipeline section; x is the current coordinate is directed along the section of the pipeline; D is the inner diameter of the pipeline; $M=\rho_0 Q_0$ is the mass flow; ρ_0 is the gas density in standard conditions, Q_0 is the volume flow of gas under standard conditions.

The soil thermal resistance is given in [24]:

$$\begin{aligned}&R_S=\ln\{(d/r_{op})+[(d/r_{op})^2-1]^{1/2}\}/(2\pi k_S),\ (d/r_{op}>2),\\&R_S=\ln(2d/r_{op})/(2\pi k_S),\ (d/r_{op}>4),\end{aligned} \quad (2)$$

where R_S is the thermal resistance of soil, (m·K)/W; d is the depth of occurrence to the centerline of the pipe, m; r_{op} is the outer radius of the pipe, m; k_S is the thermal conductivity of soil, W/(m·K).

The using is the thermal resistance of the coating in the same way as in article [19]:

$$R_P=\ln(r_Z/r_{op})/(2\pi k_P), \quad (3)$$

where R_P is the thermal resistance of the coating on the pipe surface, (m·K)/W; k_P is the thermal conductivity of the coating, W/(m·K); r_Z is the outer radius of the coating, m.

If the ambient (soil) temperature in the natural state is T_{GR}=20 °C, and the temperature in the pipe *T(z)*=30…40 °C, then such a temperature pressure environment is characteristic of the environment [25]:

$$\Delta T=T(Z)-T_{GR}=10\ldots20°C, \quad (4)$$

For spring, summer, autumn we have the thermal pressure ΔT=10…20 °C, for winter – ΔT=20…30 °C [26].

A large number of accidents corresponds to hot sections of the gas pipeline (from to 20…30 km after compressor stations) [25]. These areas are prone to corrosion failure due to the complex influence of vibration, temperature and humidity on the pipe metal in places of damage to the insulation [25, 26].

In the first stage, we evaluate the corrosion activity of the pipe-soil system from to 30 km after the compressor stations. For this purpose, we will use the devices of (BVS) and (VPP-M) and the corresponding method of measurement of potentials and corrosion currents [1, 2] on the surface of UMP (steel 17G1C).

The results of the experiment allowed us to obtain the information shown in Table 1.

Table 1. Density of corrosion current *J* as a function of distance *L* to compressor station (*CS*)

L, km	0	5	10	15	20	25	30
J, mm/year	0,2	0,31	0,35	0,40	0,43	0,30	0,13
$J_L=J/J_0$	1,54	2,38	2,69	3,08	3,31	2,31	1

In the Table 1 we have corrosion current density J_0=0,13mm/year.

In the second stage, we evaluate the corrosion activity of the pipe-soil system in the modes with impulse temperature influence according to the scheme T_{GR}=18 °C, $T(z)$=30…40°C, $\Delta T=T(z)-T_{GR}$=12… 22 °C for the distance to $L\approx30$ km from the cathode station (CS) in the same way as in articles [2–25].

The results of the experiment correspond to one year (2019) and are shown in Table 2, where N is the number of cycles (temperature fluctuations, thermal pulses). N=430 approximately corresponds to one year and the data in Table 2 refers to the situation of an underground pipe made of structural steel 17G1C which is subject to an internal vibrating hydrostatic pressure. For example, the data table. 2 refers to the distance L=30 km from the cathode station (CS) for temperature T_{GR}=18 °C, but the similar influence of thermal pulses applies to the range $L\approx0…30$ km from the cathode station (CS).

Table 2. Density of corrosion current *J* depending on number *N* of thermal pulses

N	0	86	172	258	344	430
J, mm/year	0,13	0,329	0,632	0,904	1,13	1,25
$J_T=J/J_0$	1,0	2,53	4,86	6,95	8,70	9,60
k	1	2	3	4	5	6
$\delta J=J_{Tk}/J_{T(k+1)}$		2,53	1,92	1,43	1,25	1,10

The obtained in Table 1, 2 the results in order of magnitudes and relations of type J/J_0 agree with the corresponding results in [2, 25].

The ratio δJ in table 2 characterizes the increase in the relative corrosion current density J_T and during the year δJ decreases for these Tables 2 at 2.53 / 1.1 = 2.3 times.

The thermal impulses of the compressor stations of the pipelines lead to changes in temperature $T=T(z)$ in the pipe, in particular, at a distance L=0…30 km. Consider a situation where the range L=0…30 km for a gas pipe corresponds to the temperature range $T_V=T/T_0$=3…1, where $T_0=T_{GR}$=18 °C. Such a temperature situation corresponds to the summer months [27]. The specified temperature T_V=3…1 corresponds to a similar distribution of corrosion current density. Changes in corrosion current density J_V are related to temperature T_V by Arrhenius equation and proportional to temperature [28, 29]. The corresponding distributions of temperature $T(L)$, relative corrosion current density $J_V(L)$, and density of accident $D_A(L)$ were confirmed experimentally and are shown in Table 3. The distributions $T(L)$, $J_V(L)$ and $D_A(L)$ refer to the pipeline at a distance L=0…30 km. from the compressor station (T_0=20 °C, J_*= –1,46).

Table 3. Distribution of temperature *T*, relative corrosion current density and accident density

L, km	0	5	10	15	20	25	30
$T_V=T/T_0$	3,0	2,55	2,14	1,78	1,47	1,21	1,0
$J_V=J/J_0$	3,0	2,55	2,14	1,78	1,47	1,21	1,0
$J_L=J/J_0$	1,54	2,38	2,69	3,08	3,31	2,31	1,0
$\Delta J_V=J_L-J_V$	–1,46	–0,17	0,55	1,3	1,84	1,1	0
$\Delta J_W=\Delta J_V+J_*$	0	1,30	2,02	2,77	3,31	2,57	1,46
D_A, 1/km	1,1	1,1	1,4	1,7	1,54	1,37	1,23

Here J_*= –1,46 the offset parameter; D_A is the number of accidents for an underground gas pipeline per one km [27]. The distributions T_V and J_V are proportional to each other in the same way as in [29], which found that with increasing temperature in the range T=20…80 °C the relative density of corrosion current J for a steel metal increases.

On the metal-soil boundary we consider the effect of mechanical vibrational vibrations that lead to low-cycle corrosion fatigue in the pipe [30]. The evolution equation for describing the process of small-cycle fatigue of metals on the surface (UMP) is written in the same way as in [31]:

$$\frac{dD_Z}{dt}=\left(\frac{Ee_S^2}{2\partial_S}\right)^{\lambda S} e_S^{\lambda S}\left(\frac{de_S}{dt}\right), \cdots D_Z \Rightarrow D_f\,, \tag{5}$$

where D_z , D_f is the integral volume damage of the material in the corrosive environment and its critical value; t is the time; $e_s=e_{kk}/3$ is the first invariant of the strain tensor (k = 1,2,3); λs is the empirical constant characterizing the damage; E is the modulus Young's; σ_s is the mechanical stress corresponding to the limit of corrosive fatigue for metal (steel) in the medium (soil).

5.2. Discussion of the results of the study of the distribution of corrosion current densities and accidents in the pipeline (in the monitoring system of oil and gas enterprises) for providing of safe exploitation

The procedure of estimation of thermal changes of underground pipelines with the use of model and methods taking into account by relations (1)–(4) the influence of vibrations and soil on corrosion processes on the metal surface between the pipe and the external environment is shown.

The cause of the damage to the underground pipelines is their external corrosion resulting from the contact of the metal pipes with the soil and the destruction of the protective coating layer. The locations of damage (UMP) and the corresponding corrosion currents and polarization potentials in them have been detected by type devices BVS and VPP-M [2–9]. Damage defects in pipelines arise due to the violation of the waterproofing protective layer at the metal – soil boundary.

With the help of devices BVS and VPP-M, it was established (according to Table 3) that the frequency of thermal pulses is significantly affected by the corrosion current density on the outer surface (UMP). It is established that in the range of distances from the compressor station (CS) L = 0…20 km as a result of the impact of thermal pulses, the corrosion current J_L continuously increases 2.2 times. If there were no thermal pulses from CS, then J_L would not increase but decrease [27]. At a distance L =

20…30 km from CS J_L reaches a maximum, and in the range L = 20…30 km J_L is continuously decreasing 3.3 times.

Consider two distributions $J_L(L)$and $D_A(L)$ for metal UMP, which are presented in Table 3. The determine the correlation coefficient between these distributions, in particular, it is found that K_{LD}=0,759≈0,76. The correlation is not bad, but not sufficient to establish causality between J_L and D_A. We also take into account the distribution J_V as a result of the influence of the non-fluctuating temperature background T_V and form the difference $\Delta J_V=J_L–J_V$.

The determinetion of correlation coefficient between the distributions ΔJ_V and D_A, that is K_{VD}≈0,80 for the range L=10…30 km, since the value ΔJ_V for L=0…5 km. negative. To account for the range L=0…5 km, we shift the numerical values ΔJ_V by a constant value, that is, J_*=–1,46 and obtain the distribution $\Delta J_W=\Delta J_V + J_*$ in which all numerical values are positive. In this case, between the distributions ΔJ_W and D_A the correlation coefficient K_{WD}≈0,92 for the range L=0…30 km. This correlation is significantly strong. For the correlation coefficients obtained $K_{WD} > K_{LD}$, $K_{\mathrm{WD}} > K_{VD}$, we can assume that for distributions ΔJ_W and D_A the causal relationship is quite plausible. In this case, in the first approximation, the uncertainty U of the causal relationship between ΔJ_W and D_A can be estimated by the approximate relation U_{JW}=1 – K_{WD}=0,08.

Instead of determining the data errors in Table. It is advisable to estimate uncertainty of the physical processes of the system “CS–UMP” in the soil environment, since type parameters J_L cannot be estimated accurately. General information on the uncertainty of experimental studies is presented, in particular, in [32, 33]. For a more detailed assessment of the uncertainty U_Z of the type J_L, J_V data in tables 1–3 we use formulas (1)–(4), the methods of articles [9–37], as well as the analytical relation, similar to the expression given in article [33]:

$$U_Z = U(\exp)\times U(m)\times U(r)\times U(repl)\times U(qual), \qquad (6)$$

where *U(exp)* is the uncertainty related with experimental errors; *U(m)* is the methodological uncertainty; *U(r)* is the uncertainty of result; *U(repl)=U(replication)* is the uncertainty in replicability; *U(qual)=U(quality)* is the uncertainty of system quality assessment techniques “CS–UMP” [9, 30].

In this case, based on a computational experiment, it is established that the uncertainty for the data in the Tables 1–3, taking into account the relations (1)–(5) and the methodologies of the articles [9, 30, 31] takes the value U_Z=0,09…0,1 ($U_Z > U_{JW}$).

VI. CONCLUSION

According to the results of the study such conclusions and recommendations have been formulated [1–41]:

1. The using of polarization potential meter and a contactless current meter, it is established that the frequency of thermal pulses is significantly affected by the corrosion current J_L on the outer surface of the underground metal pipeline. It is established that in the range of distances from the compressor station (CS) L = 0…20 km. as a result of the impact of thermal pulses, the corrosion current J_L continuously increases 2.2 times. At a distance L = 20 km from CS J_L reaches a maximum, and in the range L=20…30 km J_L is continuously decreasing 3.3 times.

2. Indicating the quantitative indicators of the results of the study it is found that for underground pipes made of structural steel 17G1S thermal pulses lead to an increase in the density of corrosion current J_T during the year almost 10 times. In this case, the increase in the relative corrosion current density δJ decreases and during the year for an example of a particular pipe this decrease is 2.3 times.

3. An significant correlation between the relative density of corrosion current and the density of accidents for the underground pipeline was established. As a result of this connection, the effect of thermal impulses on the distribution of corrosion current for an underground pipe within L=0…30 km from the compressor station (CS) was correctly analyzed.

4. Taking into account the quantitative indicators of the results of the study, a comparison of the relative density of corrosion current with the density of accidents for the range L=0…30 km from (CS) for a particular pipe was made. It is found that the corresponding correlation coefficient takes the value K_{WD}≈0,92 and is significant. On the basis of qualitative and quantitative information on the distribution of corrosion current at a distance L=0…30 km from CS, the main factors that disturb the reliable operation of underground pipelines of oil and gas enterprises have been identified. These are factors such as mechanical vibrations, as well as thermal impulses and electrochemical processes on the boundary between metal (steel) and soil.

5. The elements of the method of correct allocation of influence of thermal impulses on corrosion processes in the pipeline – compressor station system are offered. For this purpose, it is proposed to subtract the non-oscillating current distribution of type J_L from the total density distribution J_V of corrosive current in the range L=0…30 km at the metal boundary with the soil medium.

6. The noted information is important for improving the methods of operation of compressor stations of oil and gas enterprises taking into account the change of frequency of thermal pulses.

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