Impact of AC current density on material corrosion of distribution pipelines

Vliv střídavé proudové hustoty na korozi distribučních potrubí

Poberezhny L.[1], Maruschak P.[2], Hrytsanchuk A.[1], Mischuk B.[1], Draganovska D.[3], Poberezhna L.[4]
[1] Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine
[2] Ternopil Ivan Pul'uj National Technical University, Ternopil, Ukraine
[3] Technical University of Košice, Department of Mechanical Technology and Materials, Košice, Slovakia
[4] Ivano-Frankivsk National Medical University, Ukraine
E-mail: Maruschak.tu.edu@gmail.com

The effect of alternating induced current on the corrosion rate of steel St 3 and steel 17GS is investigated, and the electrolytes of saline soils of Ukraine are simulated. It is shown that pipe steel St 3 is more sensitive to the common corrosive action of the soil medium and induced current than steel 17GS. The most dangerous environments it terms of corrosion in the groups of chloride and chloride-sulfate electrolytes are determined.

Vliv střídavého indukovaného proudu na korozní rychlost oceli St3 a 17GS byl pozorován v simulovaných půdních elektrolytech typických pro Ukrajinu. Ocel St3 je citlivější na přirozené korozní napadení v půdě i na napadení vyvolané střídavým proudem. Byla stanovena nejhorší prostředí z hlediska koroze v elektrolytech obsahujících chloridy či směs chloridů se sírany.

INTRODUCTION

The analysis of publications on the issue of corrosion caused by alternating current [1-3] has shown that alternating current is an enhancing factor of influence during operation of pipelines in natural conditions. More significant corrosion damage to the material of the pipeline occurs as a result of the joint effect of both alternating current and ground electrolyte. If the value of the alternating current density is high, the nature of the processes that occur in the cathode and anode half-life will depend precisely on this value. At low levels of current density, the thinning rate of the pipe wall depends heavily on the corrosion factor of the medium.

In the study of electric corrosion under the influence of alternating current, one should take into account such a corrosive factor as soil. A complex interconnection between the dynamic parameters of the soil leads to a situation when a certain parameter in different combinations may not only have influence of different intensity, but also change the direction of its influence, that is, in one case act as an accelerating factor, and in the other – as a braking factor. In the case of electro-corrosion, the effect of alternating current is added to these parameters, which greatly affects the course of the anode process and indirectly affects the course of cathode processes.

When exploiting low-pressure underground gas networks, almost no attention is paid to fighting against electric corrosion under the influence of alternating current, believing that this problem only affects long-distance main gas pipelines in the adjacent passage of power transmission lines [2]. In the countries of the former Soviet Union, the distribution gas pipelines of low pressure do not have active corrosion protection.

In such conditions, with a small thickness of the pipeline wall, the formation of transient damage can occur in a very short time. Due to the imperfect application of a protective insulation coating on the pipelines, as well as the aging of insulation materials, action of aggressive media and mechanical damage, the integrity of the protective coating is impaired, and defects are formed. They can have different shapes and sizes: from small minor microcracks to large exposed sections of the metal. Due to these defects in the protective coating, there is a contact of the metal with the soil electrolyte. In addition, such exposed areas are the place of current flow and the cause of transient corrosive damage – "holes" – in the adjacent passage of pipelines with alternating current [3]. Given that the life of many pipelines is 30-40 years, i.e. the pipe material is sufficiently degraded, the time during which damage of hazardous depth is formed can be reduced significantly under the totality

of circumstances. Most dangerous for the degraded steel are acidic environments, in which the risk of hydrogenation and hydrogen cracking is high [5]. Acidic soils are common on a large part of the territory of Ukraine (Fig. 1), which further confirms the relevance of the research. The problem of the influence of alternating current on the course of corrosion processes, taking into account the component composition of soils, is studied insufficiently.
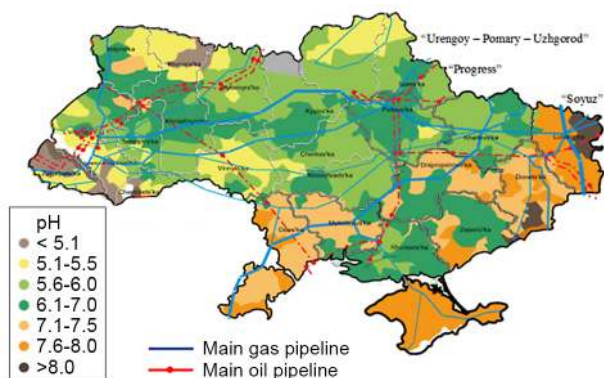

Fig. 1. Map of Ukraine's gas and oil pipelines indicating the acidity of soils
Obr. 1. Mapa Ukrajiny se zanesenými potrubními trasami a kyselostí půdy

One of the ways to increase safety of Ukraine's gas transportation system is to integrate the protection of gas pipelines from corrosion in order to prevent the occurrence of extraordinary situations.

MATERIALS AND RESEARCH TECHNIQUE

To study the electric corrosion degradation of the pipeline steel in conditions close to operating ones, a series of tests of specimens from the pipeline material was conducted in 6 model environments (Table 1). On the basis of research data, it is possible to estimate the processes of interaction that occur in the pipeline

steel in operating environments, taking into account such factor as alternating current density. The influence of the alternating current was estimated by a mass loss (kg/m^2 per year). Experimental specimens of rectangular shape measuring $50 \times 10 \times 3$ mm were made from billets cut from the walls of pipes provided by the operating organizations. The material of gas pipelines investigated was steel St 3, which is widely used in distribution gas networks, and steel 17GS, which is a common material of main gas pipelines in Ukraine.

Stray current corrosion of the pipe material caused by alternating current was studied on the setup developed and manufactured at Ivano-Frankivsk National Technical University of Oil and Gas, in the research laboratory of corrosion-mechanical degradation of materials and structures. The general view of the developed setup is shown in Fig. 2.

a)
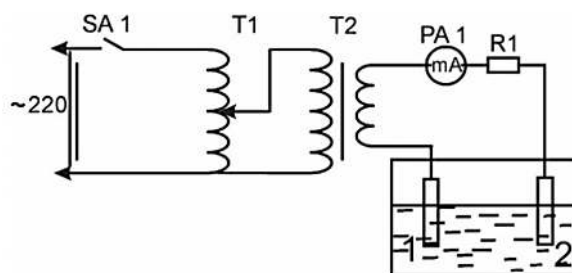
b)

Fig. 2. General view (a) and the electric diagram (b) of the setup for determining the corrosion rate in aggressive media under the influence of alternating current: SA 1 – switch, T1 – transformer TM-56, T2 – laboratory transformer LTC-500, PA 1 – ammeter, R1 – additional resistance, 1, 2 – experimental specimens
Obr. 2. Celkový pohled na experimentální uspořádání (a) a elektrické zapojení aparatury (b) pro stanovení korozní rychlosti v agresivních mediích při ovlivnění střídavým proudem: SA 1 – přepínač, T1 – transformátor TM-56, T2 – laboratorní transformátor LTC-500, PA 1 – ampérmetr, R1 – přídavný odpor, 1, 2 – vzorky

Tab. 1. Chemical composition of model environments (ME) /
Chemické složení modelových zkušebních elektrolytů

No ME	Concentration [mol l^{-1}]	
	NaCl	Na$_2$SO$_4$
1	0.01	–
2	0.05	–
3	0.1	–
4	0.005	0.005
5	0.025	0.025
6	0.05	005

The experimental setup allows to:

- set the value of current required for the experiment;
- determine the corrosion rate at different values of the stray current density;
- investigate the influence of the model environment on the course of corrosion processes;
- determine the corrosion rate in neutral and acid solutions;
- conduct visual observation over the formation of corrosion products.

The method of determining the corrosion rate under the influence of alternating current included the following steps: mechanical cleaning of specimens using fine abrasive; washing with distilled water and drying with filter paper; degreasing (toluene was used) and weighing on analytical scales with the measurement accuracy up to 0.00005 g.

Next, the specimens were fixed in the holder and immersed in pairs in the test solution (Fig. 2, b). The solutions were prepared from distilled water and chemically pure reagents of the purity class "C.P.". The immersion depth of the specimens was 2 cm, the distance between the specimens was 20 cm.

Based on the specimen area, which was immersed in the electrolyte solution, the required current density was calculated. The working area of the immersed specimen was 500 mm². The value of current density for experimental models was maintained at 5, 10, 15, 20 A m⁻². According to most international regulatory documents [9-11], current densities that exceed 10 A m⁻² are dangerous, and a similar value is adopted by Ukrainian norms [12]. The value of 5 A m⁻² is two times less than the normatively permissible value. When setting the density, the setup was connected to a voltage of 220 V, and using two converters – LATR LTC-500 and transformer TM-56 – the required current density was set in the system. The value of the current intensity was controlled by multimeter DT832.

Specimen holding time in model environments was 168 hours. The exposure time was chosen to meet the following requirements:

- repeatability of the experimental results;
- optimization of research time.

The duration of the experiment, on the one hand, makes it possible to level variations in the rate of corrosion processes associated with changes in temperature modes, and on the other hand – to quickly complete a series of experiments not only in certain types of media, but also in their full range.

To determine the influence of alternating current on the corrosion rate, we determined in parallel the corrosion rate of the control specimen (without the influence of alternating current) in the environment of similar composition and use parameter ΔK.

$$\Delta K = \frac{v_1 - v_0}{v_0} \cdot 100 \ \%,$$

where v_0 is corrosion speed of control specimen, v_1 is corrosion speed of specimen under AC.

At the end of the exposure time, the specimens were taken out of solutions, corrosion products were gummed off from their surface, the specimens were washed with distilled water and carefully dried with filter paper, and again weighed on analytical scales.

RESULTS

The results of investigations into the corrosion degradation of the pipe material in neutral chloride media ME1-3 (ME is the model environment) under the influence of alternating current indicate an intensive increase in the corrosion rate with an increase in the current density (Fig. 3). Changes in the conductivity of
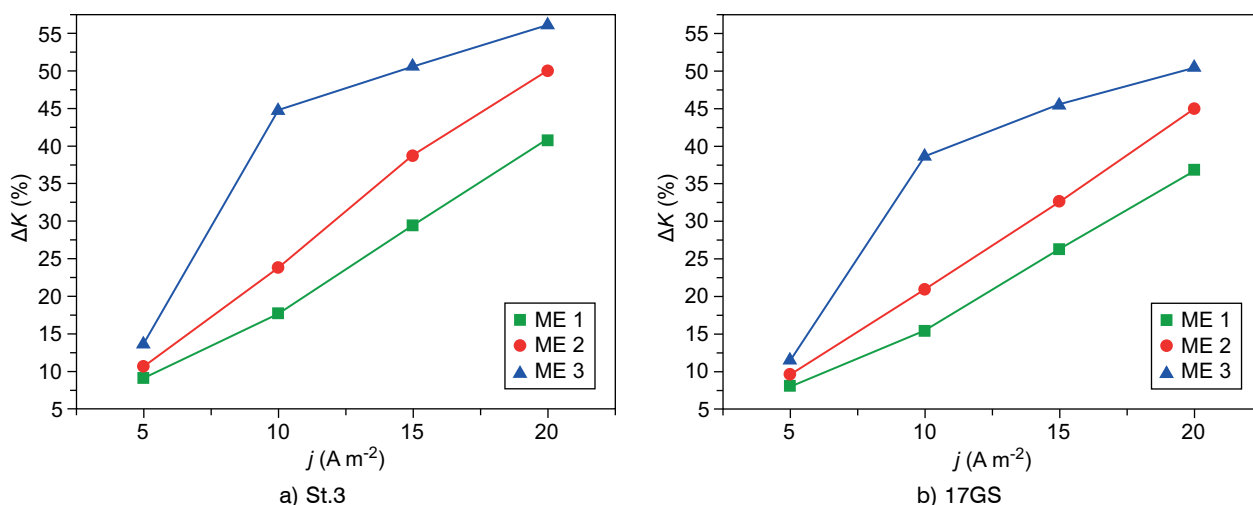

Fig. 3. Dependence of increase in corrosion rate in neutral chloride electrolytes on the value of AC density: a) St.3, b) 17GS
Obr. 3. Závislost korozní rychlosti v neutrálním chloridovém elektrolytu na střídavé proudové hustotě: a) St.3, b) 17GS

the medium are affected by the concentration of salts dissolved in ground water. In particular, an increase in the chlorides concentration leads to an increase in the electrical conductivity of the soil and a decrease in the specific resistance of the soil, which contributes to an enhanced current accumulation on pipelines.

As the concentration of chloride ions and the current density value increase, an insignificant increase in the corrosion rate in ME1 and ME2 is observed, and a slightly more intense growth is observed in the transition from ME2 to ME3. The experimentally determined acceleration at 20 A m^{-2} in ME3 is 56.1%. A significant intensification of corrosion processes is observed at the site during the transition of current density from 5 A m^{-2} to 10 A m^{-2} in ME3.

In the presence of defects in the protective coating of a small area and inadequate cathodic protection, currents with safe density as per normative documents, which accumulate in highly mineralized chloride environments, create zones of corrosion hazard, and the threat of occurrence of transient corrosion damage increases especially on pipelines that have been operated for more than 20 years and have an outdated protective coating.

With the value of current density of 5 A m^{-2} at the lowest concentration of chloride ions (ME1) the growth rate of total corrosion is 9%. With an increase in the concentration of chloride ions at a given current density, which is considered acceptable and not affecting the rate of general corrosion, the rate of general corrosion increases and accounts for 10.7% in ME2 and 13.6% in ME3, respectively. It is believed that, for values of current density less than 10 A m^{-2} (normative value), the electrochemical (ground) corrosion that occurs by the usual mechanism is predominant in the soil. An increase in the rate of general corrosion, when the density value

is half the norm, is 1.17, 1.24 and 1.43 times (Fig. 1) in ME1, ME2 and ME3, respectively. Such areas are particularly dangerous in terms of corrosion for pipelines with a wall thickness of 5 mm, if they are laid in soils with high chloride content, and there is a likelihood of alternating current.

A uniform surface corrosion is observed in ME1-3. Such damage to the surface is also characteristic of specimens not affected by alternating current (control specimens). The corrosion behavior of low-alloy steel 17GS in neutral chloride media under all values of current densities (Fig. 1b) is similar to the behavior of carbon steel St. 3. (Fig. 1a) under the given conditions. The difference between the corrosion rate of steel St. 3 and low-alloy steel 17GS ranges from 1.1 times to 1.3 times. But with the current density of 5 A m^{-2}, which is twice lower than the normatively permissible, the corrosion rate is 6.8% in ME1, 9.2% in ME2, and 11.6% in ME3.

With an increase in chloride concentration, a tendency towards a significant increase in the corrosion rate is observed, due to which the size of the damaged surface is expanding, thus facilitating the possibility of adsorption of chloride ions as a result of an increase in the actual area of the damaged zone and also because of the difficulty of the desorption process due to the increase of surface roughness. As the current density increases, a significant increase in the rate of corrosion in all neutral chloride environments is observed. A uniform increase in the corrosion rate is characteristic of the ME1 medium in the transition from the minimum value of the current density (5 A m^{-2}) to the maximum value of the current density (20 A m^{-2}). A similar tendency is typical of the ME2 environment. Deviations in this medium as compared to ME1 occur in the transition from the current density of 5 A m^{-2} to a standard value of 10 A m^{-2}. The
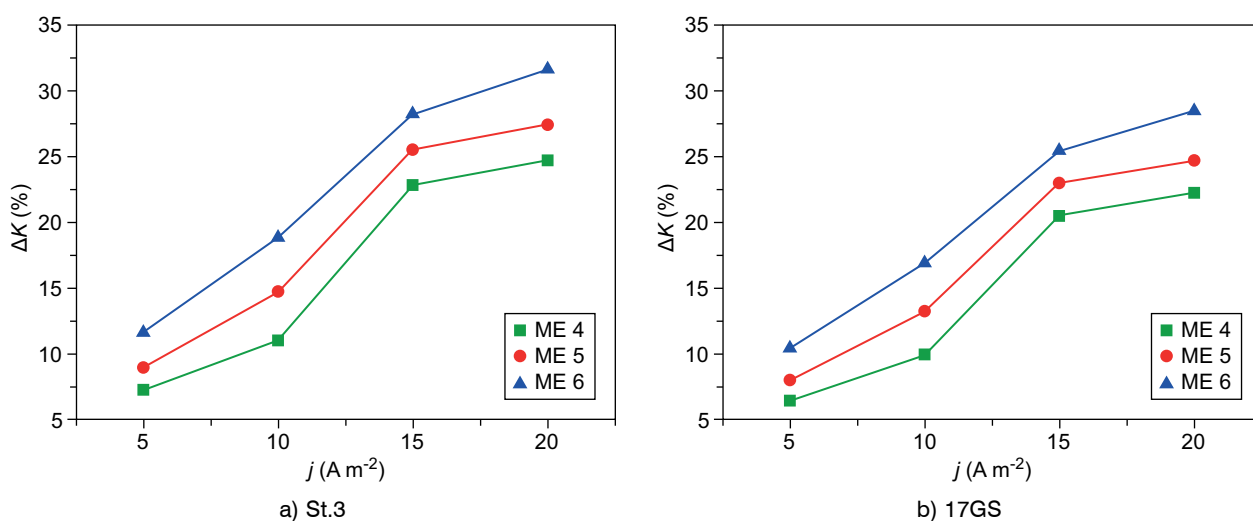

Fig. 4. Dependence of increase in corrosion rate in neutral chloride-sulfate electrolytes on the value AC density: a) St.3, b) 17GS

Obr. 4. Závislost korozní rychlosti v neutrálním chlorido-síranovém elektrolytu na střídavé proudové hustotě: a) St.3, b) 17GS

critical section for neutral chloride environments is the section obtained when determining the corrosion rate in ME3 in the transition from a current density of 5 A m^{-2} to a standard value of 10 A m^{-2}. That is, in operating conditions, when soil electrolytes contain chlorides with a concentration of 0.1 mol/l at the current density, which is even lower than the normatively permissible level, the risk of emergencies is extremely high. The negative influence of chlorides in electrocorrosion caused by alternating current is also dangerous in the presence of hydrocarbons [13]. This tendency carries operational risks for transit pipelines in Western Ukraine, where chloride and chloride-hydrocarbonate mineral waters are widespread.

High salinity regions are also characterized by soils, which in addition to chlorides contain soluble sulfates. In contrast to chloride-containing soils, the electrical conductivity of such soils somewhat decreases. The results obtained in determining the rate of corrosion in neutral chloride-sulfate media (ME4-6) have changed, accordingly.

The character of the obtained dependences shows a monotonic increase in the rate of general corrosion at all values of current density without abnormal sections or bends (Fig. 4). The maximum value of the corrosion rate at a current density of 20 A m^{-2} is 31.6%, which is 1.8 times less than the corrosion rate in ME3, where the concentration of chloride ions is the same as in ME6. A decrease in the corrosion rate is a consequence of both decreased conductivity of the medium and a change in the mechanism of processes that occur in the cathode half-life. Despite the general decrease in the corrosion rate, particular attention should be paid to the fact that for a current density of 5 A m^{-2}, the corrosion rate exceeds 5.0% and is 7.2%, 8.9% and 11.6% in ME4, ME5 and ME6, respectively.

For ME4-6, there is a surface damage characteristic of chloride-sulfate media. The rate of corrosion decreases in comparison with neutral chloride electrolytes, which can be explained by a significant accumulation of corrosion products on the specimen surface and the deceleration of oxygen diffusion before the metal surface through the layer of the formed protective film from corrosion products. This causes the localization of corrosion processes in the places of cracks and other bursting of the passive film, and often leads to the formation of deep corrosion pitches and cavities, which is also confirmed in the paper [14].

DISCUSSION

The mechanism of corrosion processes in neutral chloride and chloride-sulfate media at different values of the current density is associated with the adsorption-desorption processes that occur on the metal surface.

Chloride ions, which are available in soil electrolytes, are adsorbed in areas of damage to the insulation coating of the pipeline and destroy the protective oxide film, resulting in a passivation of the metal surface. A combination of the influence of chlorine ions, which destroy the protective film, and alternating current of the industrial frequency result in the activation of iron dissolution, transition of iron ions into the solution, and an increase in the rate of corrosion in the anode half-life. The results of experimental studies show that at a current density of 5 A/m^2 at a minimum chloride concentration, an increase in the rate of corrosion by 9.2% is observed. The results of experimental studies of the corrosion rate in neutral chloride-sulfate media obtained for 17GS steel (Fig. 2b) differ from the data for the corrosion rate of St.3 (Fig. 2a) by 1.2-1.4 times. The corrosion rate of carbon steel is slightly higher than that of low-alloy steel, but as in the case of neutral chloride media, an increase in the corrosion rate is more than 5%, which is a corrosive hazard in the case of inadequate quality of cathode protection. The corrosion rate is 5.1% in ME1, 7.6% in ME2, and 9% in ME3.

The presence of sulfates in the soil electrolytes affects the mechanism of corrosion processes and the behavior of chlorine ions. As shown by the results of experimental studies, the combined presence of chlorides and sulfates leads to a decrease in the corrosion rate in media ME4-6 as compared to chloride media. The analysis of the growth rate of corrosion of the most neutral chloride-sulfate media shows a more monotonic growth rate for all MEs than that observed in the case of neutral chloride environments (ME1-3), and the difference in the growth rate with an increase in current density is much lower than for neutral chloride media. Critical and those that require a more detailed research are the areas of transition from a current density of 10 to 15 A m^{-2}. But despite such a monotonous increase in the rate of corrosion in neutral chloride-sulfate media, the proportion of corrosion losses at a current density of 5 A m^{-2} in the percentage ratio is 7.2, 8.9, 11.6 in ME4, ME5 and ME6, respectively (Fig. 3).

The corrosion rate parameters determined experimentally allow us to estimate only the total mass loss of the metal, and the wall thinning rate is used to predict the service life of the pipeline. In order to assess the risk of depressurization, based on the results of the experimental studies, a generalized diagram was constructed (Fig. 5). Investigation of corrosion processes in neutral chloride model environments (ME1-3) showed a significant increase in the rate of general corrosion, and, consequently, the rate of relative wall thinning with an increased chloride-ion concentration and current density. A slightly lower increase in the corrosion rate is observed at different current densities in ME1 and ME2. A sharp increase in these parameters is observed in ME3 for a current density of 10 A m^{-2}, which in accordance with

the normative documents of Ukraine is a permissible norm. Insulation coating of the pipeline may be damaged at the stage of laying, and its quality deteriorates with time, contributing to an increase in the number of exposed areas. In the absence or inadequate quality of cathodic protection of the main pipelines in chloride environments, the thinning rate of the wall in accordance with Fig. 5 can reach a value of 0.23 mm/year in ME1, 0.32 mm/year in ME2 as early as at a current density of 5 A/m², and in the case of ME3 will exceed 0.47 mm/year, which is 9.0%, 10.7%, 13.6% respectively. These values indicate the need for an early review of the level of permissible current density in the Ukrainian anti corrosion protection regulations.

The study of the wall thinning rate in neutral chlo-ride-sulfate media (ME4-6) showed a reduction in the corrosion rate compared to ME1-3, which can be explained by a lower mobility of sulfate ions, and, consequently, a decrease in conductivity. In these environments there is a monotonic increase in the rate of corrosion processes without sharp jumps.

In further research, it is planned to simulate electric corrosion under the action of alternating current for long-operated cathode-protected pipelines [15], where the induction of alternating current may cause additional flooding of the surface in cathode sections.

CONCLUSIONS

The effect of alternating induced current on the corrosion rate of the material of low and medium pressure pipelines is investigated, and the electrolytes of saline soils of Ukraine are simulated. It is shown that pipe steel St 3 is more sensitive to the common corrosive action of the soil medium and induced current than steel 17GS.

The most dangerous environments it terms of corrosion in the groups of chloride and chloride-sulfate electrolytes are determined.
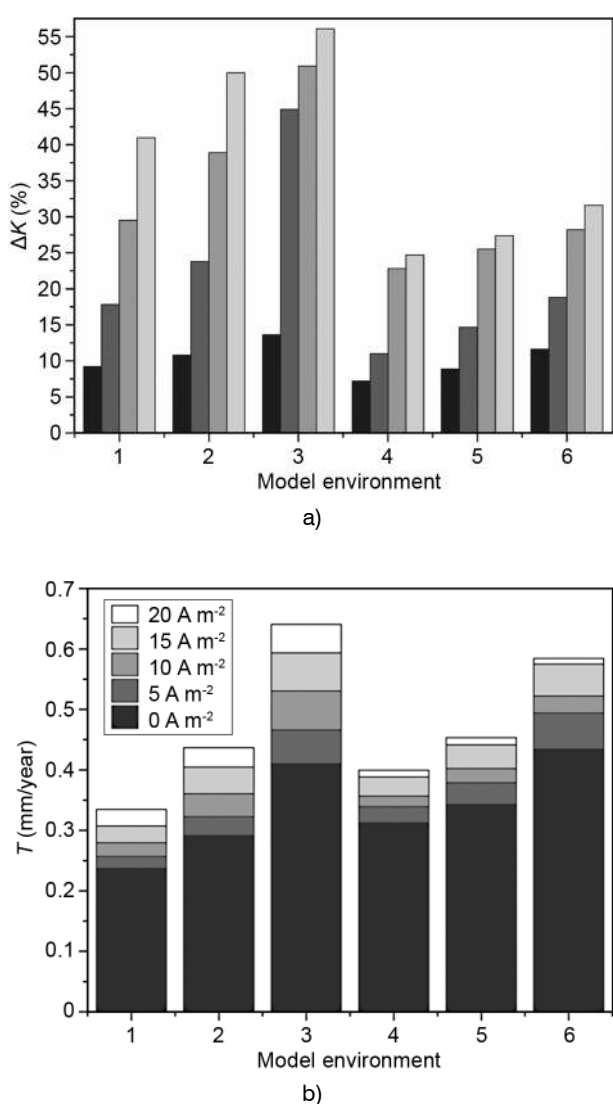

Fig. 5. Dependence of increase in corrosion rate (a) and the wall thinning (b) in neutral chloride and chloride-sulfate electrolytes on the value of current density
Obr. 5. Závislost nárůstu korozní rychlosti (a) a úbytku tloušť-ky trubky (b) v neutrálním chloridovém a chlorido-síranovém elektrolytu na střídavé proudové hustotě

REFERENCES

1. Hamlin A.W. Some effects of alternating current on pipeline operations, *Materials Performance* **1980**, 19, 18-27.
2. Dunn D.S., Bogart M.B., Brossia C.S., Cragnolino G.A. Corrosion of iron under alternating wet and dry conditions, *Corrosion* **2000**, 56 (5), 470-481.
3. von Baeckmann W., Schwenk W., Prinz W. *Handbook of Cathodic Corrosion Protection*, 7 - Edition, Gulf Publishing House, Houston, Texas, 1997, 151 p.
4. 9th Report of the European Gas Pipeline Incident Data Group (period 1970-2013) https://www.egig.eu/startpagina. (*accessed 5 Dec 2017*).
5. Jones D.J.: Principles and prevention of corrosion, Mcmillan Publishing Company, N.Y., 1992.
6. Fiedorowicz, M; Jagiełło, M. Korozja przemiennopradowa a ochrona katodowa podziemnych rurociagów, IX Krajowa Konferencja Pomiary korozyjne w ochronie elektrochemicznej 9th National Conference Corrosion measurements in electrochemical protection 7-9. 06. 2006 Zakopane, Poland.
7. Burnham, A., Han, J., Clark, C. E., Wang, M., Dunn, J. B., & Palou-Rivera, I. (2011). Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environmental Science and Technology* **2011**, 46 (2), 619-627.
8. Tsyrul'nyk, O. T., Nykyforchyn, H. M., Petryna, D. Y., & Dz'oba, I. M. Hydrogen degradation of steels in gas mains after long periods of operation. *Materials Science* **2007**, 43 (5), 708-717.
9. PN-EN 12954:2004 "Ochrona katodowa konstrukcji metalowych w gruntach lub w wodach. Zasady ogólne i zastosowania dotyczące rurociągów".

10. CEN/TS 15280, "Evaluation of a.c. corrosion likelihood of buried pipelines – Application to cathodically protected pipelines", Technical Specification, CEN – European Committee for Standardization, 2006.

11. NACE SP0177, "Mitigation of alternating current and lightning effects on metallic structures and corrosion control systems", NACE International Standard Practice, 2007.

12. DSTU B V.2.5-29: 2006 "General requirements for corrosion protection. Underground steel gas pipelines".

13. Goidanich S., Lazzari L., Ormellese M. AC corrosion. Part 2: Parameters influencing corrosion rate, *Corrosion Science* **2010,** 52, 916-922.

14. Fu A.Q., Cheng Y.F. Effects of alternating current on corrosion of a coated pipeline steel in a chloride-containing carbonate/bicarbonate solution, *Corrosion Science* **2010**, 52, 612-619.

15. Maruschak P., Danyliuk I., Prentkovskis O. Degradation of the main gas pipeline material and mechanisms of its fracture, *J. Civ. Eng. Manag.* **2014**, 20, 864-872.