

Modeling the resistance of plate-like heat exchangers made of 06khn28mdt alloy (analogous to aisi904l steel) to crevice corrosion in recycled water enterprises

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This study investigates the mechanisms and patterns of crevice corrosion in heat exchangers made from 06KhN28MDT alloy (analogous to AISI 904L steel) in model water systems of industrial enterprises. Using mathematical models, the relationship between activation potentials (E_{crev}), repassivation potentials (E_{rep}), and free corrosion potentials (E_{cor}) with the alloy's chemical composition and structural components was established. It was found that E_{crev} shifted positively with increasing levels of Mn, Cr, Cu and d_g (mean austenite grain diameter), and decreasing levels of C, Si, Ni, Ti, Mo, V_s (sulfide volume), and V_N (titanium nitride volume). Cr, Mo, and d_g were identified as having the most significant influence on E_{crev} , E_{rep} and E_{cor} . The study also highlights the importance of chromium in improving the protective properties of the oxide film, and the reduction of local corrosion damage near titanium carbonitrides intersecting austenite grain boundaries. The study concludes that the alloy's resistance to crevice corrosion in recycled water systems improves with higher concentrations of Cr, Mo, and d_g . The mathematical models developed in this research can be applied to predict the corrosion resistance of heat exchangers made from 06KhN28MDT alloy in industrial water systems.

Key words: 06KhN28MDT alloy heat exchanger, crevice corrosion, recycled industrial water, selective metal dissolution.

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1. Introduction

Plate heat exchangers made of 06KhN28MDT alloy are often used for the production of acids, such as sulfuric, hydrofluoric, stearic, phosphoric, etc. [1]. To cool process products, which are solutions of these acids, water from the recycling systems of enterprises is used. It contains chloride ions and other activators of local corrosion of passivated steels and alloys [2, 3]. This can cause pitting and crevice corrosion of heat exchange equipment in such media. Many studies have been devoted to determining and predicting the resistance of heat exchangers to pitting corrosion in recycled water [4-8]. In particular, the authors of [5] modeled the corrosion behavior of austenitic steels in chloride-containing media during the operation of plate-like heat exchangers, papers [6,7] are devoted to establishing the patterns and mechanisms of pitting corrosion of heat exchangers

during its operation in chloride-containing media, and [9] to the influence of specific magnetic susceptibility on the corrosion losses of steel from pitting. And in [10, 11], the authors investigated the relationship between corrosion losses of the 06KhN28MDT alloy in model reservoir waters of oil and gas fields in Kazakhstan, depending on its chemical composition and structure components. Academician L.I. Rosenfeld determined the similarity of pitting and crevice corrosion patterns [12], but the latter has some characteristic features. That is, in the paper investigated the patterns and mechanisms of crevice corrosion of plate-like heat exchangers made of 06KhN28MDT alloy in the recycled water of enterprises, using the analysis of the developed mathematical models that establish the relationship between the alloy's ultimate electrochemical performance and its chemical composition within the standard and the structure components.

2. Materials and methods of research

Five industrial melts of the 06KhN28MDT alloy, which is used to produce heat exchanger plates with

a thickness of 0.3- 1.2 mm, were studied. The chemical composition of the alloy and the components of its structure (table 1) have been determined in [8].

Table 1 – Real sample based on sample research results

№ swimming trunks	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	E _{cor} , V	E _{crev} -V	Err, V	ΔE, V
1	0,05	0,32	0,6	24,31	27,39	0,79	2,9	2,75	0,1711	0,0091	11	-0,4	1,1	0,8	1,2
2	0,067	0,46	0,57	22,68	27,65	0,59	2,78	2,68	0,1427	0,0036	24	-0,43	0,58	0,5	0,93
3	0,068	0,54	0,55	21,84	27,45	0,55	2,55	2,6	0,1918	0,0043	29	-0,42	0,58	0,22	0,64
4	0,048	0,57	0,62	22,67	27,73	0,67	2,56	2,53	0,1692	0,0043	31	-0,4	1,1	0,55	0,95
5	0,05	0,31	0,57	23,46	27,51	0,89	2,51	2,78	0,0931	0,0036	15	-0,38	1,13	0,6	0,98
min	0.048	0.31	0.55	21,84	27,39	0,55	2,51	2,53	0,0931	0,0036	11	-0.5	0.4	0.1	
max	0.068	0.57	0.62	24,31	27,73	0,89	2,9	2,78	0,1918	0,0091	29	-0.1	1.2	0.7	
multiplicity	0.001	0.01	0.01	0,01	0,01	0,01	0,01	0,01	0,0001	0,0001	1	0,01	0,01	0,01	0,01

where: x₁ – C, carbon content in steel, wt. %;
 x₂ – Mn, manganese content in steel, wt. %;
 x₃ – Si, silicon content in steel, wt. %;
 x₄ – Cr, chromium content in steel, wt. %;
 x₅ – Ni, nickel content in steel, wt. %;
 x₆ – Ti, titanium content in steel, wt. %;
 x₇ – Mo, molybdenum content in steel, wt. %;
 x₈ – Cu, copper content in steel, wt. %;
 x₉ – volume of nitrides, % V = 0.0931 – 0.1918, vol. %;
 x₁₀ – Volume of sulfides, % V = 0.0036 – 0.0091, vol. %;
 x₁₁ – d_g, μm, mean austenite grain diameter: d = 11-31μm;
 E_{cor} – free corrosion potential, V;
 E_{crev} – activation potential, V;
 E_{rep} – repassivation potential, V;
 ΔE is the criterion defined as E_{rep} – E_{cor}, V.

The variance of deviations in the content of the alloy components is: for carbon ± 0.002, silicon ± 0.004, manganese ± 0.01, chromium ± 0.02, nickel ± 0.03, molybdenum ± 0.02, copper ± 0.02, titanium ± 0.02, phosphorus ± 0.02, sulfur ± 0.003 wt. %.

Polished samples 30x20x10mm with a hole 06 mm were collected in bags. A gap of 0.3 mm was set between the sample and the counterbody (the size of the gap between adjacent plates of plate-like heat exchangers, which was fixed with fluoroplastic washers). Electrochemical studies were performed on a P5848 potentiostat. The setup

consisted of test samples made of 06KhN28MDT alloy with a thickness of 1 mm, a counter body made of the same alloy, a saturated chlorosilver comparison electrode, a Lugin capillary, an auxiliary electrode made of platinum, a fluoroplastic bolt and nut, cathode voltmeter (input resistance not less than 5 mV, measuring range not less than ±1V, counting accuracy not less than 5 mV), microammeter (current measuring range from 0.1 MA to 10 MA) and thermostat for maintaining the temperature in the range of ±1°C (Fig. 1).

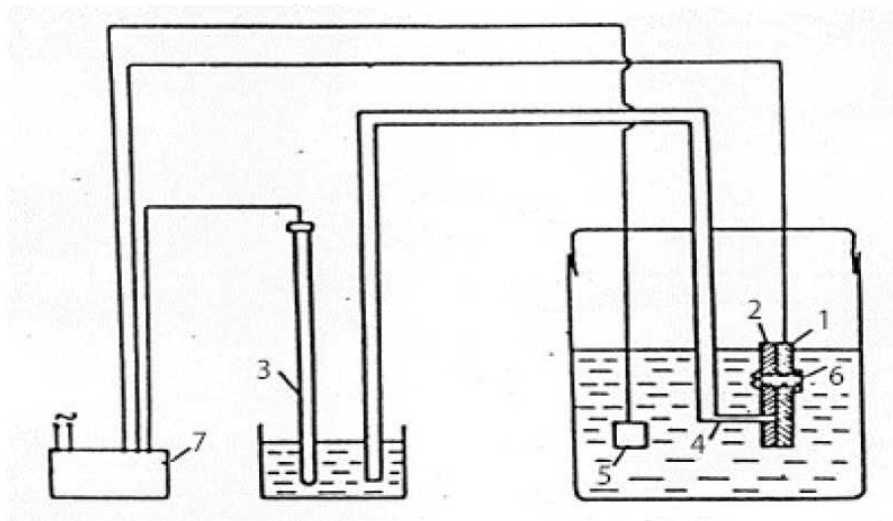


Figure 1 – Schematic diagram of the setup for electrochemical studies of 06KhN28MDT alloy in a chloride-containing solution of 3% NaCl: 1 – sample; 2 – counterbody; 3 – comparison electrode; 4 – Lugin capillary; 5 – auxiliary electrode; 6 – fluoroplastic bolt and nut; 7 – potentiostat P 5848.

The sample was immersed for 30 minutes in the solution, which was repeatedly passed through a Lugin capillary and a gap. Prior to polarization, the samples were kept in the solution for 10 minutes until the steady-state potential was established and anodically polarized at a rate of 1.8 V/hour. The forward and reverse potentiodynamic curves were taken until the current density (30 mA/cm^2), and the reverse curves until the minimum cathodic currents (0.005 mA/cm^2) were recorded. The deviation of the activation potentials E_{crev} and repassivation potentials E_{rep} in the crevice did not exceed $\pm 0.01 \text{ V}$. The crevice corrosion resistance of 06KhN28MDT alloy was evaluated by ΔE , a criterion determined by the difference between the repassivation potential E_{rep} and the free corrosion potential E_{cor} . The alloy was considered to be resistant to crevice corrosion if $\Delta E > 0.05 \text{ V}$ [13]. The alloy's E_{crev} potential in the crevice was used as an additional criterion for assessing the alloy's crevice corrosion resistance in model recycled water. The electrochemical parameters of the 06KhN28MDT alloy are shown in Table 1. The

generated variable ($x_1 \dots x_{11}$) and output factors (E_{cor} , E_{rep} , E_{crev} , and ΔE) are shown in Table 2.

Multivariate linear regressions were used as the basis for constructing mathematical models [14]. The first-order multivariate linear regression equation is as follows:

$$y^s = \sum_{j=1}^N B_j x_j^s, y = 1, 2, \dots, S, \quad (1)$$

where y^s is the value of the initial characteristic for the s -th observation of the sample

(E_{cor} , E_{rep} , E_{crev}), °C,

B_j is the weight of the j -th feature,

S is the number of sample instances.

The quality of the model was assessed by the sum of squared instantaneous mistakes (2):

$$E = \sum_{s=1}^S (y^s - y^{s*})^2, \quad (2)$$

where: y^s is the actual value of the output feature for the s -th observation of the training sample;

y^{s*} is the estimated value of the output feature for the s -th observation of the training sample.

Table 2 – Generated sample

s	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	E _{corrs} , V	E _{crevs} , V	E _{rp} , V
1	0.0500	0.3200	0.6000	24.3100	27.3900	0.7900	2.9000	2.7500	0.1711	0.0091	11.0000	-0.4000	1.1000	0.8000
2	0.0670	0.4600	0.5700	22.6800	27.6500	0.5900	2.7800	2.6800	0.1427	0.0036	24.0000	-0.4300	0.5800	0.5000
3	0.0680	0.5400	0.5500	21.8400	27.4500	0.5500	2.5500	2.6000	0.1918	0.0043	29.0000	-0.4200	0.5800	0.2200
4	0.0480	0.5700	0.6200	22.6700	27.7300	0.6700	2.5600	2.5300	0.1692	0.0043	31.0000	-0.4000	1.1000	0.5500
5	0.0500	0.3100	0.5700	23.4600	27.5100	0.8900	2.5100	2.7800	0.0931	0.0036	15.0000	-0.3800	1.1300	0.6000
6	0.0570	0.3100	0.5900	23.3300	27.6100	0.6700	2.7000	2.7100	0.1807	0.0039	13.0000	-0.4100	0.6600	0.3300
7	0.0610	0.5100	0.6200	22.1500	27.5100	0.7800	2.6600	2.7500	0.1219	0.0043	23.0000	-0.4300	0.3900	0.3200
8	0.0520	0.5400	0.6000	22.8800	27.3900	0.6000	2.6200	2.7500	0.1524	0.0054	16.0000	-0.4100	0.6800	0.3600
9	0.0570	0.5400	0.6100	23.0900	27.6000	0.7900	2.5200	2.6700	0.0977	0.0059	19.0000	-0.3900	1.0000	0.5400
10	0.0480	0.3300	0.6100	23.1600	27.5100	0.6700	2.5700	2.5700	0.1277	0.0054	25.0000	-0.3800	1.2700	0.7300
...														
40	0.0550	0.4300	0.5800	23.5200	27.5800	0.7700	2.7000	2.6300	0.1402	0.0040	18.0000	-0.4000	1.0300	0.6500
41	0.0670	0.5100	0.6000	23.7300	27.6500	0.8400	2.8100	2.7700	0.1041	0.0058	20.0000	-0.4000	1.1000	0.8700
42	0.0530	0.3200	0.6200	23.6300	27.4400	0.6000	2.7800	2.6300	0.1006	0.0059	14.0000	-0.4000	0.9000	0.7300
43	0.0640	0.5500	0.5500	23.4500	27.6200	0.6400	2.8400	2.6000	0.0958	0.0041	25.0000	-0.4100	1.1000	0.9500
44	0.0620	0.5100	0.5900	23.8800	27.4000	0.6900	2.6100	2.6500	0.1800	0.0051	22.0000	-0.3700	1.6300	0.8500
45	0.0490	0.3500	0.6100	22.3200	27.6700	0.6600	2.7700	2.5400	0.1656	0.0063	28.0000	-0.4400	0.5000	0.4200
46	0.0540	0.4100	0.5600	24.2200	27.5400	0.5800	2.7900	2.6600	0.1255	0.0077	26.0000	-0.3700	1.7600	1.2200
47	0.0530	0.4500	0.5800	22.2300	27.5900	0.8700	2.5500	2.7500	0.1474	0.0060	14.0000	-0.4300	0.1500	0.0300
48	0.0530	0.4300	0.5900	22.7200	27.6500	0.8500	2.8000	2.6300	0.1527	0.0071	13.0000	-0.4500	0.1100	0.1800
49	0.0580	0.3900	0.5900	24.1700	27.5400	0.5600	2.8700	2.7600	0.1285	0.0050	25.0000	-0.3900	1.5900	1.1900
50	0.0580	0.4600	0.6000	22.0700	27.6900	0.8700	2.5500	2.7400	0.1829	0.0037	20.0000	-0.4300	0.2400	-0.0200

3. Research results and discussion

A multifunctional mathematical model (3) was developed using Equation (1) and the generated sample of events (Table 2). It establishes the relationship between the repassivation potential of the 06KhN28MDT alloy (E_{rep}) and its chemical composition ($x_1 \dots x_9$) and structure components ($x_9 \dots x$):

$$E_{rep} = -0.8136x_1 - 0.031x_2 + 0.0763x_3 + 0.3664x_4 - \\ - 0.3319x_5 - 0.0991x_6 + 0.2813x_7 + \\ + 0.1055x_8 - 1.8513x_9 + 1.3326x_{10} + 0.027x_{11}, \quad (3)$$

The quality of the constructed mathematical model (3) was evaluated using Formula 2, in particular, SSE is 0.0915 and MSE is 0.0018V. Thus, it adequately describes the relationship between the repassivation potential of the 06KhN28MDT alloy and its chemical composition and structure components and can be used to assess and predict the resistance of heat exchangers to crevice corrosion.

According to the results of the analysis of the constructed mathematical model (3), it can be noted that the repassivation potential E_{rep} of the studied alloy shifts in a positive direction with an increase in the content of silicon, chromium, molybdenum, copper, the volume of titanium sulfides, the mean grain diameter of austenite, and a decrease in the content of carbon, manganese, nickel, titanium, and the volume of titanium nitrides. It should be noted that the variables ($x_1 \dots x_{11}$) of the mathematical model (3) have a different effect on the potential E_{rep} of the alloy in the gap. In particular, according to model (3) and data (Table 1), it was found that it shifts to the positive side by 0.005; 0.905; 0.11; 0.03; 0.007; and 0.54V with an increase in the content of Si, Cr, Mo, Cu, the volume of titanium sulfides, and the mean austenite grain diameter in the intervals given in (Table 1). At the same time, it was found that the potential E_{rep} of the 06KhN28MDT alloy shifts by 0.016; 0.0002; 0.113; 0.034; 0.046V in the negative direction with an increase in the content of C, Mn, Ni, Ti, and the volume of titanium nitrides in the intervals given in Table 1. It should be noted that C, Mn, Si, and the volume of titanium sulfides practically do not affect the repassivation potential E_{rep} of the studied alloy in the gap, since it can change within the measurement mistake ($\pm 0.01V$) when these parameters change in the mentioned intervals (Table 1). Thus, it can be noted that the intensity of the

influence of the parameters of the 06KhN28MDT alloy on its potential E_{rep} in the gap increases in the following order: Cu; Ti; volume of titanium nitrides (V_N); Mo; mean austenite grain diameter (d_g); Cr. At the same time, it should be noted that Mo, Cr, and the mean austenite grain diameter of the alloy have an order of magnitude greater effect on the potential E_{rep} than Cu, Ti, and the volume of titanium nitrides. This is consistent with the data from [15-19] on the ability of Cr and Mo to form mixed oxide films on the surface of stainless steels and alloys that actively counteract its local activation by chloride ions. Rosenfeld I.L. [12] and Todt F. [15] believed that Cr and Mo are the most effective alloying elements that increase the corrosion resistance of steels in chloride-containing media. It is believed [20] that Mo increases the resistance of passive films to "breakdown" in chloride-containing media, improves passivation characteristics, and reduces the rate of metal dissolution in pitting [21]. Papers [22-24] found that in model recycled waters where plate heat exchangers are operated, the critical pitting temperature of AISI321 and AISI304 steels increases with an increase in their chromium content, while the other chemical elements in its composition do not affect it. Paper [7] found that the pitting resistance of the 06KhN28MDT alloy depends on the parameters of the chloride-containing media, its structure components, and the content of chromium, and the effect of Mo on the critical temperature of its pitting was not found. However, it is believed in [16] that Mo improves the protective properties of passive films in neutral solutions due to the adsorption of MoO_4^{2-} ions on them, which are formed as a result of the oxidative dissolution of molybdenum from steel and displacement chloride ions from its surface. In our opinion, the mechanisms of local corrosion of the 06KhN28MDT alloy described in [22-24] are inherent in low- mineralized chloride-containing media, such as recycled water from enterprises. Indeed, under such conditions, the number of metastable pitting on the alloy surface decreases, which can contribute to the transformation of the remaining ones that have not been repassivated into stable ones due to the redistribution of the anode current density. Thus, we believe that under such conditions, Mo does not increase the resistance of the oxide film on the surface of the 06KhN28MDT alloy to the activating effect of chloride ions, but it promotes the repassivation of localized corrosion damage on its surface in the crevice, shifting the

repassivation potential to the positive side by 0.11V, as mentioned above. This increases the ΔE - criterion of the alloy, which indicates its resistance to crevice corrosion. However, it should be noted that chromium has an 8.2-fold stronger effect on the repassivation potential of the alloy under study than Mo. It is known [2, 3] that localized corrosion damage on the surface of steels and alloys originates and develops in the vicinity of inclusions. In addition, stable pitting occurs and develops in the vicinity of inclusions of a certain nature [26-28] and size [29], which are in contact with the boundaries of austenite grains [2, 3]. Therefore, according to dependence (3), the potential E_{rep} of the 06KhN28MDT alloy shifts to the positive side with an increase in the mean diameter of the austenite grain and a decrease in the volume of titanium nitride inclusions in the vicinity of which pitting in the gap mainly originated. After all, the bigger d_g and the smaller the size of these inclusions, the less likely they are to intersect.

A multidimensional mathematical model (4) was constructed that establishes the relationship between the free corrosion potential E_{cor} of the 06KhN28MDT alloy in the crevice and its chemical composition ($x_1 \dots x_8$) and structure components ($x_9 \dots x_{11}$).

$$E_{cor} = 0.285x_1 - 0.0032x_2 + 0.0304x_3 + 0.0325x_4 - 0.0324x_5 - 0.0026x_6 - 0.1131x_7 + 0.0002x_8 - 0.0301x_9 - 0.1464x_{10} + 0.0013x_{11}; \quad (4)$$

The quality of the mathematical model (4) was evaluated using formula (2), in particular, $SSE=0.0028282$ and $MSE=0.0000057B$. Thus, it adequately establishes the relationship between the potential E_{cor} of the studied alloy and its chemical composition and structure components. According to the results of the analysis of the mathematical model (4), it can be noted that the free corrosion potential E_{cor} of this alloy shifts to the positive side with an increase in the content of C(x_1); Si(x_3); Cr(x_4); Cu(x_8) and the mean austenite grain diameter (x_{11}) and a decrease in Mn(x_2), Ni(x_5); Ti(x_6); Mo(x_7) and the volume of nitrides (x_9) and titanium sulfides (x_{10}). However, the intensity of the influence of these factors on the potential E_{cor} of the alloy under study is very different. In particular, it was found that it shifts to the positive side by 0.0057, 0.021, 0.0803, 0.00005, and 0.026 V with an increase in the content of C, Si, Cr, Cu, and the mean diameter of the austenite grain in the intervals indicated in Table 1. In particular, this potential (E_{cor}) of the alloy shifts to

the negative side by 0.0008, 0.011, 0.0009, 0.044, 0.003, 0.0008 V with an increase in the content of Mn; Ni; Ti and the volume of titanium nitrides and sulfides in the intervals indicated in (Table 1). It was found that the intensity of the influence of the chemical composition and the structure components of the studied alloy on its free corrosion potential (E_{cor}) increases in the following order: d_g , Mo, Cr. It can be noted that these alloying elements and the mean austenite grain diameter have the greatest effect on the potentials E_{cor} and E_{rep} of the 06KhN28MDT alloy in the gap. At the same time, the influence of Cr, Mo, and d_g on the alloy repassivation potential in the gap E_{rep} is 11.3, 2.5, and 20.8 times, respectively, greater than on the free corrosion potential E_{cor} . It should be noted that ΔE , a criterion by which the resistance of steels and alloys to crevice corrosion is evaluated [13], of the 06KhN28MDT alloy increases by 0.15 V with an increase in its Mo content (Table 1). Thus, it turns out that Mo effectively increases the resistance of 06KhN28MDT alloy to crevice corrosion in model recycled water, contributing to a shift in the repassivation potential of the alloy (E_{rep}) to the positive side and free corrosion E_{cor} to the negative side. At the same time, the alloying of the studied alloy with Cr has a more effective effect on its resistance to crevice corrosion in a chloride-containing medium, since its ΔE criterion increases by 0.825 V with an increase in its Cr content from 21.84 to 24.34 wt.% (Table 1).

Summarizing the above, it can be noted that the 06KhN28MDT alloy is resistant to crevice corrosion in model recycled water. It is due to high content of Cr and Mo.

The activation potential of the 06KhN28MDT alloy in the gap (E_{crev}), according to [13], is proposed as an additional criterion for assessing its resistance to crevice corrosion in model recycled water. For this purpose, a multidimensional mathematical model (5) was constructed, which establishes the relationship between this potential (E_{crev}) of the alloy under study and its chemical composition ($x_1 \dots x_9$) and structure components ($x_9 \dots x_{11}$) (Table 1).

$$\Delta E_{crev} = -4.1448x_1 + 0.0198x_2 - 1.0528x_3 + 0.5981x_4 - 0.3620x_5 - 0.4513x_6 - 0.9145x_7 + 0.1009x_8 - 1.3369x_9 - 9.811x_{10} + 0.0325x_{11}; \quad (5)$$

The quality of the constructed mathematical model (5) was estimated by formula (2), in particular, $SSE = 0.6497$ and $MSE = 0.0130$ V. Consequently,

this model adequately establishes the relationship between the potential E_{crev} of the 06KhN28MDT alloy in the gap and its chemical composition and structural components. According to the results of the analysis mathematical model (5), it was found that the potential E_{crev} of the studied alloy shifts to the positive side with an increase in the content of Mn(x_2); Cr(x_4); Cu(x_8) and the mean austenite grain diameter (x_{11}) and decreasing – C(x_1); Si(x_3); Ni(x_5); Ti(x_6); Mo(x_7), the volume of nitrides(x_9) and titanium sulfides (x_{10}). It should be noted that they affect this potential with different intensities, since it shifts to the positive side by 0.108, 1.477, 0.025, and 0.65 V with an increase in the content of Mn(x_2); Cr(x_4); Cu(x_8) and the mean austenite grain diameter (x_{11}), respectively, in the intervals indicated (in Table 1). At the same time, it was found that the E_{crev} potential shifts to the negative side by 0.082, 0.074, 0.123, 0.153, 0.357, 0.132, and 0.054 V with an increase in the content of C(x_1) in the alloy; Si(x_3); Ni(x_5); Ti(x_6); Mo(x_7), the volume of nitrides (x_9) and titanium sulfides (x_{10}), respectively, in the intervals indicated in (Table1). It was found that the intensity of the influence of the chemical composition of the 06KhN28MDT alloy ($x_1 \dots x_8$) and its structure components ($x_9 \dots x_{11}$) on the potential E_{crev} increases in the following order: Cu content (x_6), volume of titanium sulfides (x_{10}); Si content (x_3); C (x_1); Mn (x_2); Ni (x_5); volume of titanium nitrides (x_9); Ti content (x_6); Mo (x_7), mean austenite grain diameter (x_{11}), Cr content. It should be noted that Cr, Mo, and the mean austenite grain diameter have the greatest effect on the repassivation potential (E_{rep}), free corrosion (E_{cor}), and activation of the 06KhN28MDT alloy in the crevice (E_{crev}). At the same time, Cr has a 1.6 and 18.5 times more intense effect on the E_{crev} potential than E_{rep} and E_{cor} , respectively. At the same time, it should be noted that the mean austenite grain diameter has a 1.2 and 25 times more intense effect on E_{crev} than E_{rep} and E_{cor} , respectively. Taking into account the above, it can be noted that the probability of local corrosion damage in the vicinity of titanium nitrides at the intersection with the boundaries of austenite grains has almost the same effect on the E_{crev} and E_{rep} potentials of the 06KhN28MDT alloy in a chloride-containing media. This is due to the fact that the resistance of the oxide film to activation by chloride ions in these areas of the alloy and the influence of its structure imperfections on the repassivation of local corrosion damage are equivalent factors. But it should be noted that the

effect of Mo on the potential repassivation E_{rep} of the alloy is twice as high as Cr, which is consistent with the data from [21, 22].

It was found that the activation potential E_{crev} of the 06KhN28MDT alloy in the crevice noticeably shifts to the negative side with an increase in the content of C (-0.008 V), Si (-0.07 V), Mo (-0.357 V), and Ti (-0.451 V) in the interval indicated in (Table 1). This is most likely due to the precipitation of Mo and Ti carbides in the vicinity of titanium nitrides, where pittings were born. This is consistent with the data of [29], which states that an increase in the Ti content in stainless steels reduces the potential region corresponding to the passive state. Under such conditions, an increase in current density was recorded on the anode polarization curves. This is attributed [30] to the ability of carbides, especially Ti, Mo, and Nb, to accelerate the ionization of hydrogen ions on them, which helps to accelerate anodic processes associated with the ionization of metals in localized corrosion damage. Taking into account the data from [31], the facilitated activation of the 06KhN28MDT alloy in the gap is most likely due to the promotion of Si to precipitate carbides from the solid solution of the alloy austenite. A noticeable shift in the potential E_{crev} of the studied alloy to the negative side (-0.13V) with an increase in titanium nitride inclusions in the interval indicated in (Table 1) is most likely due to the precipitation of Mo and Ti carbides in their vicinity. After all, it shifts to the negative side by 0.082 V with an increase in the C content in the alloy, which created carbides with Mo and Ti. Obviously, the effect of Ti and especially Mo dissolved in a solid solution of austenite on the potential E_{crev} is stronger than that of its carbides. This, taking into account the data in [2], may be due to the acceleration of the solid-phase diffusion of Fe atoms to the surface of local corrosion damage on the surface of the 06KhN28MDT alloy in the gap. It is likely that the shift of the potential E_{crev} of this alloy in the negative direction (-0.12 V) with an increase in its Ni content is also associated with the acceleration of the solid-phase diffusion of Fe atoms to the surfaces of local corrosion damage, which contributed to their growth. The analysis of the mathematical model (5) also shows that the effect of titanium sulfides on the potential E_{crev} of the alloy in the gap is close to Ti and Mo carbides in the vicinity of nitrides titanium, but half as much as these nitrides themselves. This is due to the fact that Mo and Ti sulfides are generally insoluble in acidic media [32], which are formed in the gap and localized corrosion

damage due to hydrogenation of alloy corrosion products.

Summarizing the above, it can be noted that the potential E_{crev} of the 06KhN28MDT alloy, unlike E_{cor} and E_{rep} , depends on many chemical composition and structure elements. It shifts to the positive side with an increase in the content of Mn, Cr, Cu, d_g and a decrease in C, Si, Ni, Ti, Mo, and the volume of titanium sulfides and nitrides. This dependence is due to the improvement of the protective properties of chromium-containing oxide films on the surface of the studied alloy and reducing the likelihood of local corrosion damage pitting carbonitrides titanium carbonitrides, where the overvoltage of hydrogen ionization in acidic media formed in the crevice is reduced. It was found that the potential E_{cor} of the studied alloy shifts to the positive side with an increase in the content of Si, Cr, Mo, Cu, V_S , d_g and a decrease in C, Mn, Ni, Ti and V_N , but the influence of the parameters C, Mn, Si and V_S is very low. It has been established that the potential E_{rep} of the 06KhN28MDT alloy shifts to the positive side with an increase in the content of C, Cr, Cu, d_g and a decrease in Mn, Ni, Ti, Mo, V_N , V_S . It has been found that Cr, Mo and d_g have the greatest influence on the potentials E_{crev} , E_{rep} and E_{cor} . At the same time, the higher they are, the higher the resistance of the alloy to crevice corrosion in model recycled water. The constructed mathematical models can be used for to evaluate i prediction resistance of heat exchangers made of 06KhN28MDT alloy to crevice corrosion during their operation in recycled water of enterprises.

4. Conclusion

Multifactorial mathematical models have been built that establish the relationship between the activation potentials E_{crev} , repassivation E_{rep} , and free corrosion E_{cor} of the 06KhN28MDT alloy depending on its chemical composition and structure components in model recycled water. It has been found that the potential E_{crev} of the alloy shifts to the positive side with an increase in the content of Mn, Cr, Cu, d_g and a decrease in C, Si, Ni, Ti, Mo, V_S , V_N . It was found that the potential E_{cor} potential of the alloy shifts to the positive side with an increase in the content of Si, Cr, Mo, Cu, V_S , d_g and a decrease in C, Mn, Ni, Ti, and V_N , but the influence of C, Mn, Si, and V_S is very low. It has been shown that the potential E_{rep} of the alloy shifts to the positive side with an increase in the content of C, Si, Cr, Cu, d_g and a decrease in Mn, Ni, Ti, Mo, V_N and V_S .

At the same time, it was found that Cr is 1.6 and 1.8 times and d_g is 1.2 and 25 times more intensively affected by the E_{crev} potential than by E_{rep} and E_{cor} , respectively. However, the effect of Mo on the E_{rep} potential is twice as large as that of Cr. It is shown that Cr, Mo and d_g have the greatest influence on the potentials E_{crev} , E_{rep} , and E_{cor} . At the same time, it was found that the influence of Cr, Mo, and d_g on E_{crev} is 1.6 and 143.5; Mo is 3.2 and 8.1; and d_g is 1.2 and 2.5 times greater than on E_{rep} and E_{cor} , respectively. It is shown that the resistance of the 06KhN28MDT alloy to crevice corrosion increases with an increase in the content of Cr, Mo, and the mean diameter of the austenite grain.

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