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DEVELOPMENT AND PERFORMANCE EVALUATION OF A SYNERGISTIC COMPOSITE INHIBITOR AGAINST ELECTROCHEMICAL AND MICROBIOLOGICALLY INFLUENCED CORROSION

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This study is devoted to evaluating the protective performance of a newly developed composite inhibitor system under complex corrosion conditions involving sulfate-reducing bacteria (SRB) and electrochemically active components. The main objective was to design synergistic composite inhibitors that provide high protection efficiency at low concentrations. Among the individual reagents tested, «Neftqaz-2013» exhibited 90% corrosion protection efficiency in an electrochemical environment at a concentration of 1.0 mg/L, but its activity was limited under microbiological conditions. Specifically, the growth rates of Desulfovibrio and Desulfomicrobium SRB strains reached 78% and 80%, respectively, while the concentration of biogenic hydrogen sulfide decreased only to 77 mg/L. Conversely, the «MARZA-1» reagent showed relatively weak bactericidal action against SRB; even at the highest dosage, the growth rates remained within 82–84%, and the H_2S level decreased to 38 mg/L. To overcome these limitations, both reagents were combined in different ratios to obtain a series of complex NMK-type compositions. Among them, the NMK-3 composition (1:19 ratio) provided the best performance, ensuring 98% corrosion protection in an electrochemical medium and 99% and 97% inhibition of Desulfovibrio desulfuricans and Desulfomicrobium strains, respectively, at a concentration of 7.0 mg/L. Under these conditions, the biogenic H_2S concentration was reduced to 18 mg/L. Gravimetric and microbiological analyses were conducted in accordance with ASTM G31, GOST 9.913-90, and NACE TM0172 standards. The results demonstrated that, unlike individual reagents, synergistic composite inhibitor systems exhibit superior performance against both electrochemical and microbiological corrosion, indicating their strong potential for industrial application.

Keywords: corrosion, inhibitor, microbiologically influenced corrosion, electrochemical corrosion, sulfate-reducing bacteria, synergistic composite.

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Introduction

In modern industrial sectors, particularly in oil and gas production, transportation, and processing, ensuring the long-term service life of metallic equipment and structures requires highly effective protection against corrosion.

Corrosion, defined as the gradual degradation of materials, primarily metals, due to chemical or electrochemical interaction with the environment, leads to substantial economic losses, technological safety risks, and environmental pollution across various industries. Accordingly, numerous technological and chemical strategies have been developed to combat corrosion, among which the use of corrosion inhibitors

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is one of the most widespread approaches [1–4].

Corrosion inhibitors are chemical compounds that, even in small concentrations, extend the service life of materials by forming protective films on metal surfaces or by retarding the electrochemical reactions involved in the corrosion process. However, the efficiency of these inhibitors strongly depends on their chemical nature, the characteristics of the corrosive medium, and their mechanism of action.

In the petroleum industry, the environments where corrosion occurs are often not only electrochemical in nature but also microbiologically active. In particular, microbiologically influenced corrosion (MIC) caused by sulfate-reducing bacteria (SRB) represents a widespread and highly hazardous problem in formation waters and oil transportation systems [5–7].

SRB are mainly microorganisms belonging to the genera Desulfovibrio and Desulfomicrobium, which reduce sulfate ions to hydrogen sulfide (H_2S) under anaerobic conditions. H_2S generated through their metabolic activity acts as a highly aggressive corrosive agent that reacts with metallic surfaces, leading to deformation, perforation, and eventual failure.

In addition to such microbiological effects, the presence of ions and other reactive components in the surrounding medium intensifies electrochemical corrosion processes [8–10].

In complex environments where microbiological and electrochemical influences act synergistically, the use of single-function inhibitors, those targeting only one mechanism (either microbiological or electrochemical), is often insufficient. Therefore, the development of multifunctional inhibitors capable of simultaneously mitigating both microbiological and electrochemical corrosion is an urgent scientific and practical task.

Such inhibitors must neutralize aggressive chemical agents while also suppressing microbial activity. This integrated approach not only prevents corrosion but also enhances the overall biological stability and operational safety of the system.

Within this framework, various compositions were prepared based on the well-known industrial electrochemical inhibitor «Neftqaz-2013» and the nitrogen–halogen-containing experimental reagent «MARZA-1», which exhibits microbiological activity. The individual and combined effects of these reagents were investigated, and the synergistic potential of their mixtures under corrosive conditions was evaluated.

The goal of developing these compositions was to combine the adsorption and protective properties of both reagents to achieve high inhibition efficiency in environments subject to both electrochemical and microbiological corrosion.

In the experimental phase of this study, the protective action of the inhibitors was assessed using gravimetric and electrochemical methods, while the growth rate of SRB was monitored through microbiological analysis. In addition, the variation of biogenic hydrogen sulfide concentration was evaluated to determine the influence of individual and composite inhibitors on bacterial activity and H_2S generation [11,12].

The results demonstrated that the optimally formulated NMK-3 composition exhibited high protection efficiency in both corrosion environments, confirming the potential of complex inhibitor systems for integrated corrosion control.

This introduction provides the scientific rationale of the study, its relevance to the current problem, and the justification for the chosen methodology. The subsequent sections present a detailed analysis of experimental results, comparative evaluation of the synthesized compositions, and their potential for large-scale industrial application.

Experimental

For the cultivation and testing of sulfate-reducing bacteria (SRB), a nutrient medium of the «Postgate B» type was used, which provides active growth of *Desulfomicrobium* and *Desulfovibrio desulfuricans* strains. The chemical composition of the medium is presented in Table 1. The pH value was maintained within the range of 7.0–7.5 and verified using a universal indicator.

The population density of SRB was determined by the serial dilution method, and cell counts were observed microscopically using an MBI-6 optical microscope.

To evaluate the effect of the tested reagents on the growth of sulfate-reducing bacteria (SRB), cultures were incubated under thermostatic conditions at 35^0C for 15 days. The formation of biogenic hydrogen sulfide (H_2S) was determined by the iodometric titration

Table 1

Composition of the «Postgate B» medium

Component	NH_4Cl	K_2HPO_4	$MgSO_4 \cdot 7H_2O$	$CaSO_4$	Ca lactate	Na_2S	Na_2SO_3	$FeSO_4$ (5% solution in 1% HCl)
Content, g/L	1.0	0.5	2.0	1.0	2.6	0.2	2.0	0.5

method, while the visual identification of microbial activity was carried out based on the appearance of a characteristic black precipitate.

In contrast, in samples containing reagents with bactericidal activity, a white precipitate was observed, indicating the suppression of SRB growth.

The quantitative assessment of SRB populations and the determination of the inhibitory efficiency were performed according to the following formula [1,13]:

$$M = \frac{1000 \cdot a \cdot n}{h \cdot s},$$

where M is the number of cells in 1 mL of suspension; a is the average number of cells counted within one square of the hemocytometer grid; h is the depth of the counting chamber (mm); S is the area of the grid square (mm^2); and n is the dilution factor of the bacterial suspension.

The growth rate (N, %) of SRB cells in the presence of a reagent was determined using the following formula:

$$N,\% = \frac{n_0 - n_{inh}}{n_0} \cdot 100\%,$$

where n_0 is the number of SRB cells in the control (reagent-free) medium; and n_{inh} is the number of SRB cells in the sample containing the tested reagent.

Steel specimens of Ct3 grade were used in the experiments (Table 2). Prior to testing, the samples were mechanically cleaned, weighed, and subjected to corrosion tests under standard conditions.

The corrosion rate in aggressive laboratory media was calculated according to the following relationship [1,13]:

$$K = \frac{m_1 - m_2}{S \cdot \tau},$$

where m_1 is the weight of the steel specimen before the experiment (g); m_2 is the weight of the steel specimen after removing corrosion products (g); S is the surface area of the steel specimen (m^2); and τ is the test duration (h).

In corrosion studies, the inhibition coefficient (or corrosion retardation factor) is also used, which is determined according to the following relationship:

$$\gamma = \frac{K_0}{K_{inh}},$$

where K_0 is the corrosion rate in the blank (without reagent) ($g/m^2 \cdot h$); and K_{inh} is the corrosion rate in the presence of the reagent ($g/m^2 \cdot h$).

The inhibition coefficient (corrosion retardation factor) is calculated as:

$$Z = \frac{K_0 - K}{K_0} \cdot 100\%,$$

where K_0 is the in the blank (without reagent) ($g/m^2 \cdot h$); and K is the corrosion rate in the presence of the reagent ($g/m^2 \cdot h$).

Another term used in corrosion studies is the penetration rate (depth loss per unit time), which is determined as follows:

$$K_P = \frac{\Delta m}{\rho \cdot S \cdot \tau},$$

where Δm is the mass loss; ρ is the metal density; S is the exposed area; τ is the exposure time; and K_P is the penetration rate (thickness loss).

Two domestically produced corrosion inhibitors were employed for the experimental investigations. One of these, «Neftqaz-2013», is widely used in the oil and gas industry for protecting the internal surfaces of equipment against corrosion; its technical specifications are presented in Table 3.

The theoretical technical profile of the «MARZA-1» reagent can be summarized as follows. «MARZA-1» is a liquid-phase reagent formulated on the basis of unsaturated organic compounds containing nitrogen functionality in combination with a halogen-bearing moiety. Structurally, it contains C, H, O, and halogen elements. Owing to its chemical architecture, particularly the presence of nitrogen together with halogen functionality, the reagent is reactive toward electrochemical corrosion processes and simultaneously exhibits resistance to microbiological effects.

Its color is theoretically light brown to yellowish. In an inert aqueous medium, the pH is 7–8, providing a neutral to slightly alkaline environment. The pour point is estimated to be below -20^0C, enabling operability at low temperatures. «MARZA-1» is miscible

Table 2

Constituents of Ct3 grade steel

Constituent	C	Mn	Si	P	S	Cr	Ni	Cu	Fe
Content, wt.%	0.2	0.5	0.15	0.04	0.05	0.30	0.20	0.20	98.36

with aliphatic and aromatic solvents, which enhances its technological versatility and facilitates integration into various systems. The reagent is expected to display high bactericidal activity, with a synergistic inhibitory effect against sulfate-reducing bacteria (SRB), notably strains of *Desulfovibrio* and *Desulfomicrobium*. «MARZA-1» is intended primarily for protection against microbiological degradation in oil and gas processing systems.

Results and discussions

Preliminary investigations began with an assessment of the protective performance of the widely used industrial corrosion inhibitor «Neftqaz-2013» against electrochemical corrosion. For this purpose, H_2S-bearing formation water was employed as the test medium. The optimal inhibitor concentration and the corresponding laboratory results are summarized in Table 4.

The results in Table 4 summarize the electrochemical corrosion protection efficiency of the «Neftqaz-2013» inhibitor in H_2S-bearing formation water. During testing, carbon-steel specimens were exposed for 24 h to inhibitor solutions at concentrations of 0.4, 0.7, and 1.0 mg/L; a 0 mg/L blank served as the control. These data indicate a pronounced, concentration-dependent reduction in corrosion rate, demonstrating effective protection by «Neftqaz-2013». The highest protection was observed at 1.0 mg/L, consistent with suppressed electrochemical kinetics and strengthened adsorption-controlled inhibition.

In the next stage, the microbiological protection afforded by «Neftqaz-2013» was evaluated using Postgate B nutrient medium to monitor the growth of sulfate-reducing bacteria. The test strains belonged to *Desulfovibrio desulfuricans* and *Desulfomicrobium*. The influence of different inhibitor concentrations on the SRB growth rate was examined, and concentration-dependent changes in bacterial activity were recorded. The corresponding results are presented in Figures 1 and 2. The data show that increasing inhibitor concentration did not completely suppress bacterial growth. Even at the maximum concentration of 1.0 mg/L, the growth rate of *Desulfovibrio desulfuricans* remained at 78%, while that of *Desulfomicrobium* was 80%.

These findings indicate that the microbiological effect of «Neftqaz-2013» is limited and that achieving complete inhibition would require either higher dosages or the use of composite inhibitors. Thus, while «Neftqaz-2013» partially reduces microbial activity, it alone is insufficient for full suppression of SRB under the tested conditions.

For comparative analysis, the influence of different concentrations of the «MARZA-1» reagent on the growth of sulfate-reducing bacteria (*Desulfovibrio desulfuricans* and *Desulfomicrobium*) was also investigated. The dependence of bacterial growth rate on inhibitor concentration is presented in Figures 3 and 4. In both cases, bacterial growth increased with concentration, reaching 82% for *Desulfo vibrio desulfuricans* and 84% for *Desulfomicrobium* at the maximum concentration of 10 mg/L. These results indicate that the microbiological activity of «MARZA-1» is limited, and that even at elevated concentrations, bacterial activity is not completely suppressed.

The conducted experiments demonstrated that when used individually, neither «Neftqaz-2013» nor «MARZA-1», could provide maximum protection efficiency: neither in H_2S-rich formation waters nor

Table 3

Physicochemical properties of the «Neftqaz-2013» inhibitor

Parameter	Value
aggregate state	liquid
color	light brown
density (at 20^0C)	0.9514 g/cm^3 (≈951.4 kg/m^3)
kinematic viscosity (at 20^0C), cSt	20.81
pour point (freezing point), ^{0}C	–46
pH	9–10
flash point, ^{0}C	38

Table 4

Corrosion inhibition performance of «Neftqaz-2013» in H_2S-containing formation water

C_{inh},mg/l	K_0, g/m^2·h	K_{inh}, g/m^2·h	γ	K_p, mm/year	Z, %
0	1.3840	–	0	–	0
0.4	–	0.4429	3,12	0,496	68
0.7	–	0.2214	6,25	0,248	84
1.0	–	0.1384	10	0,155	90

in microbiological environments dominated by sulfate-reducing bacteria (*Desulfovibrio desulfuricans* and *Desulfomicrobium*). Therefore, to achieve higher efficiency in both types of corrosive environments, the two reagents were combined in different ratios to produce synergistically active composite formulations. The main advantage of these compositions lies in their ability to integrate the specific adsorption and protective properties of each component. These dual-action mixtures exhibited enhanced protection against both electrochemical and microbiological corrosion while maintaining high efficiency at lower total concentrations.

Table 5 presents the provisional designations, compositional ratios, and overall concentrations of the newly developed composites prepared on the basis of the «Neftqaz-2013» and «MARZA-1» reagents, which demonstrated higher effectiveness compared to individual inhibitors. For all compositions, the total concentration was fixed at 7 mg/L, with variations only in the relative proportions of the two components: «Neftqaz-2013» and «MARZA-1».

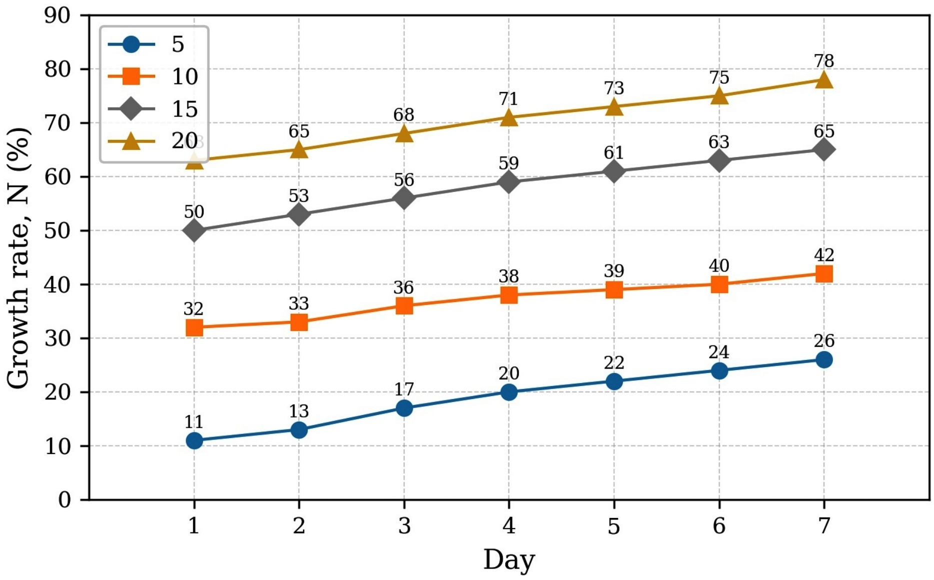

Fig. 1. Effect of Neftqaz-2013 concentration on the growth rate N (%) of *Desulfovibrio desulfuricans* ($C_{Neftqaz-2013}$=0.3, 0.5, 0.8, and 1.0 mg/L)

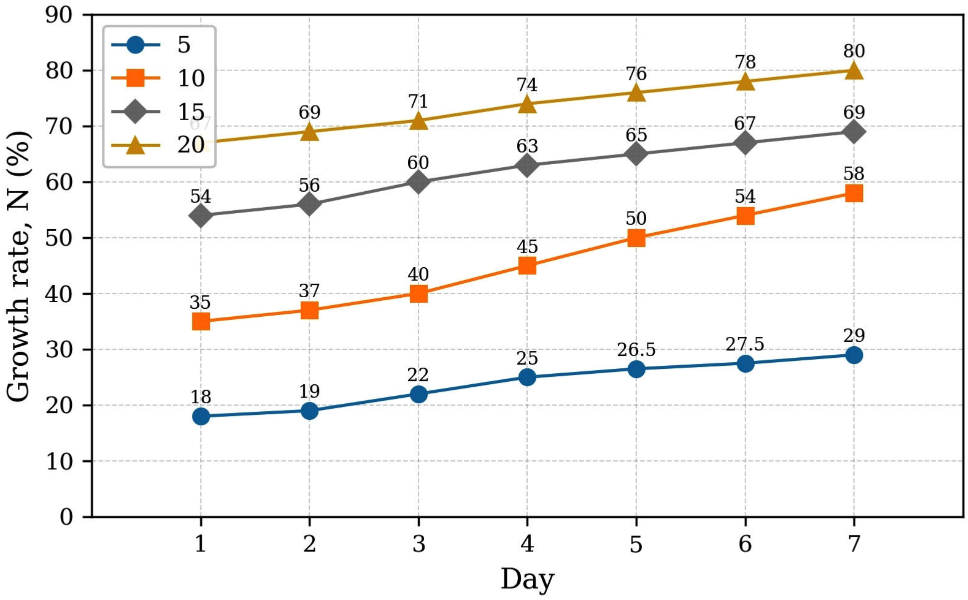

Fig. 2. Effect of Neftqaz-2013 concentration on the growth rate N (%) of *Desulfomicrobium* ($C_{Neftqaz-2013}$=0.3, 0.5, 0.8, 1.0 mg/L)

As in the case of individual inhibitors, the initial tests of the complex compositions were carried out in H_2S-containing formation water, focusing mainly on mass loss and corrosion rate at the metal surface. For comparative analysis, five selected compositions were examined by the gravimetric method, and the experimental results were systematically summarized in Tables 6–10.

Experimental results showed that in all compositions, mass loss and corrosion rate decreased significantly with increasing concentration, while the protection efficiency rose proportionally.

The NMK-1 composition («Neftqaz-2013»: «MARZA-1»=1:27) provided 92% protection efficiency at a total concentration of 7.0 mg/L. Due to the higher proportion of «MARZA-1», this formulation can be recommended for mild or passive corrosion environments.

The NMK-2 composition (1:22.3) achieved 94% protection efficiency, demonstrating satisfactory performance in electrochemical media.

The NMK-3 composition (1:19) exhibited the maximum protection efficiency of 98% at 7.0 mg/L, confirming that the synergistic effect between «Neftqaz-2013» and «MARZA-1» is maximized at this optimal ratio.

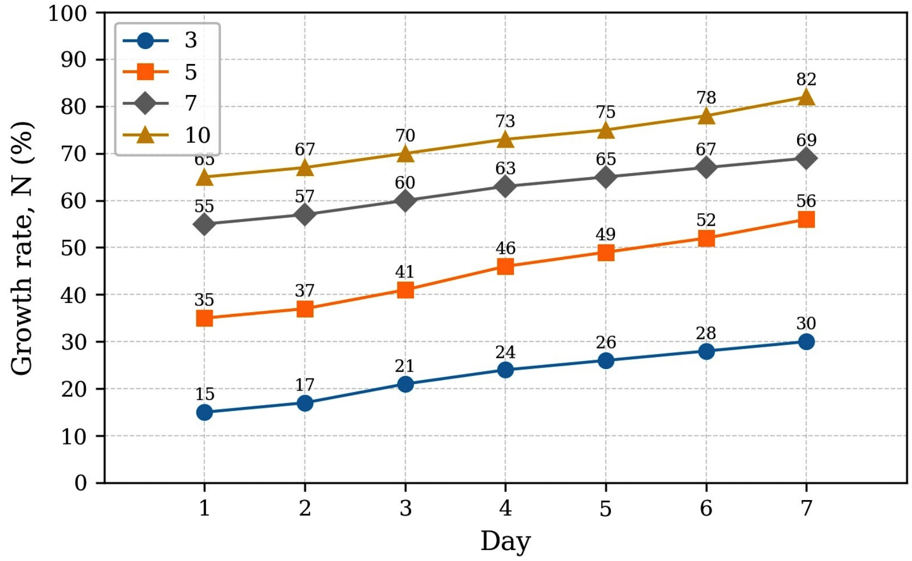

Fig. 3. Effect of MARZA-1 concentration on the growth rate N (%) of *Desulfovibrio desulfuricans* ($C_{MARZA\text{-}1}$=3, 5, 7, 10 mg/L)

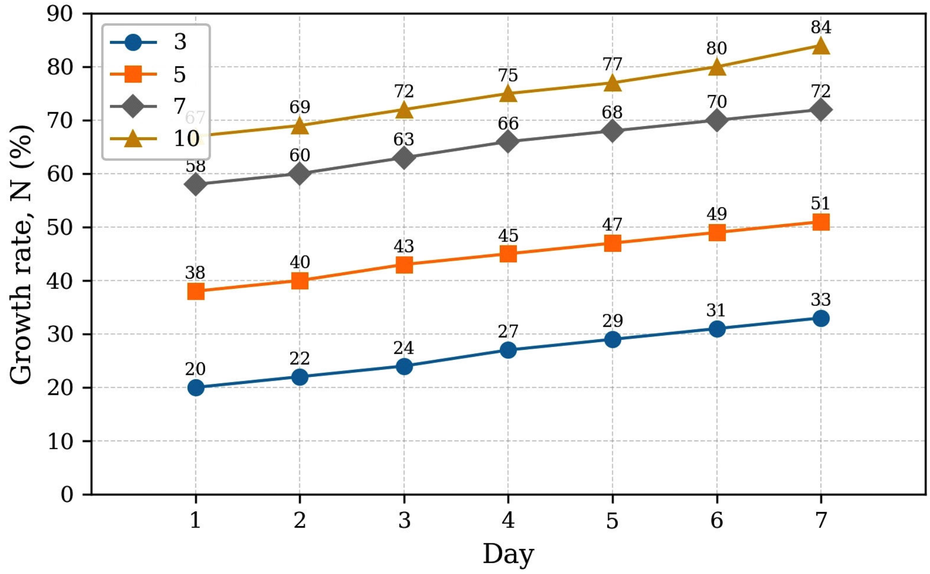

Fig. 4. Effect of MARZA-1 concentration on the growth rate N (%) of *Desulfomicrobium* ($C_{MARZA\text{-}1}$=3, 5, 7, 10 mg/L)

Table 5

Designations, component ratios, and total concentrations of newly developed synergistic inhibitor compositions (NMK series)

Designation	Components	Ratio	Concentration
NMK-1	Neftqaz-2013+MARZA-1	1:27	7 mg/L
NMK-2	Neftqaz-2013+MARZA-1	1:22.3	
NMK-3	Neftqaz-2013+MARZA-1	1:19	
NMK-4	Neftqaz-2013+MARZA-1	1:16.5	
NMK-5	Neftqaz-2013+MARZA-1	1:14.6	

Table 6

Corrosion inhibition performance of NMK-1 in H_2S-containing formation water

C_{inh},mg/l	K_0, g/m^2·h	K_{inh}, g/m^2·h	γ	K_p, mm/year	Z, %
0	1.3840	–	–	–	0
2.0	–	0.3875	3.57	0.434	72
4.5	–	0.1799	7.69	0.201	87
7.0	–	0.1107	12.5	0.124	92

Table 7

Corrosion inhibition performance of NMK-2 in H_2S-containing formation water

C_{inh},mg/l	K_0, g/m^2·h	K_{inh}, g/m^2·h	γ	K_p, mm/year	Z, %
0	1.3840	–	0	–	0
2.0	–	0.3322	4.17	0.372	76
4.5	–	0.1384	10	0.155	90
7.0	–	0.0830	16.67	0.009	94

Table 8

Corrosion inhibition performance of NMK-3 in H_2S-containing formation water

C_{inh},mg/l	K_0, g/m^2·h	K_{inh}, g/m^2·h	γ	K_p, mm/year	Z, %
0	1.3840	–	0	–	0
2.0	–	0.2629	5.26	0.294	81
4.5	–	0.0968	14.29	0.108	93
7.0	–	0.0277	49.96	0.031	98

Table 9

Corrosion inhibition performance of NMK-4 in H_2S-containing formation water

C_{inh},mg/l	K_0, g/m^2·h	K_{inh}, g/m^2·h	γ	K_p, mm/year	Z, %
0	1.3840	–	0	–	0
2.0	–	0.3045	4.55	0.341	78
4.5	–	0.1246	11.11	0.139	91
7.0	–	0.0692	20	0.078	95

Table 10

Corrosion inhibition performance of NMK-5 in H_2S-containing formation water

C_{inh},mg/l	K_0, g/m^2·h	K_{inh}, g/m^2·h	γ	K_p, mm/year	Z, %
0	1.3840	–	0	–	0
2.0	–	0.2076	6.67	0.233	85
4.5	–	0.1107	12.5	0.124	92
7.0	–	0.0554	24.98	0.062	96

The NMK-4 composition (1:16.5) provided 95% protection, making it suitable for more aggressive electrochemical environments.

Finally, the NMK-5 composition (1:14.6) achieved 96% protection, characteristic of systems with a higher proportion of «Neftqaz-2013».

Overall gravimetric analyses indicated that NMK-3 was the most efficient formulation, ensuring both the highest protective performance and the lowest metal loss. These findings confirm that combining «Neftqaz-2013» and «MARZA-1» in a 1:19 ratio enables complex and effective protection against electrochemical corrosion, highlighting the potential of such composite systems for industrial application.

Subsequently, the study was extended to evaluate the microbiological protection capabilities of these compositions in Postgate B nutrient medium, containing sulfate-reducing bacteria of the genera *Desulfovibrio desulfuricans* and *Desulfomicrobium*. The effect of varying composition concentrations (3.0–7.0 mg/L) on bacterial growth rate was examined, and the obtained results are illustrated in Figures 5 and 6.

Analysis of the results obtained from the study of the microbiological effects of composite inhibitors revealed that all NMK-series compositions significantly restricted the growth of bacterial cells with increasing concentration. For both bacterial species, *Desulfovibrio desulfuricans* and *Desulfomicrobium*, the maximum inhibitory effect was observed at a concentration of 7 mg/L.

In particular, the NMK-3 composition exhibited inhibition efficiencies of 99% and 97%, respectively, for *Desulfomicrobium* and *Desulfovibrio desulfuricans*, confirming its superior performance in suppressing microbiological activity. Although NMK-2 and NMK-5 also demonstrated high efficiency (93–95%), NMK-3 presented the most balanced ratio in terms of synergistic interaction and stable microbiological effectiveness.

The NMK-1 and NMK-4 compositions provided slightly lower but still satisfactory protection (90–92%). These results indicate that the microbiological efficiency of compositions containing MARZA-1 and Neftqaz-2013 depends not only on the total concentration but also critically on the relative ratio of their components.

Overall, the findings confirm the effectiveness of complex inhibitor systems in mitigating microbiologically influenced corrosion (MIC) and highlight the industrial potential of NMK-3 as a promising formulation.

Furthermore, since high concentrations of biogenic hydrogen sulfide (H_2S) accelerate the corrosion process, variations in the H_2S concentration were also investigated under reagent-free conditions, as well as in the presence of individual inhibitors («MARZA-1» and «Neftqaz-2013») and their composite formulations. The corresponding results are presented in Fig. 7.

Based on the data presented in Fig. 7, the influence of individual reagents and their composite formulations on the concentration of biogenic hydrogen sulfide (H_2S) is shown comparatively. It should be noted that, for each reagent and composition, the experiments were conducted at their respective optimal concentrations.

In the blank medium (without inhibitor), the H_2S concentration reached 270 mg/L, indicating an intense sulfidogenic process. The individual inhibitors «Neftqaz-2013» and «MARZA-1» reduced this value to 77 mg/L and 38 mg/L, respectively. However, more pronounced results were obtained with the composite inhibitors.

In particular, the NMK-3 composition (1:19 ratio, 7.0 mg/L concentration) achieved the lowest H_2S concentration of 18 mg/L, while other formulations (NMK-1, NMK-2, NMK-4, and NMK-5) produced comparable results within the 24–25 mg/L range.

These findings once again confirm that composite inhibitors, when formulated at optimal ratios and concentrations, can effectively minimize the risk of microbiologically influenced corrosion not only by protecting metal surfaces but also by reducing sulfide generation. Thus, such compositions offer a promising approach for controlling biogenic H_2S in industrial systems.

Conclusions

1. The research results demonstrated that the combination of the Neftqaz-2013 and MARZA-1 inhibitors at specific ratios, particularly the NMK-3 composition (1:19, 7.0 mg/L), provided up to 99% protection efficiency in an electrochemical corrosion environment. This outcome is attributed to the synergistic interaction between the components, which enhances both adsorptive stability and inhibitor kinetics. Such a synergistic approach outperformed individual reagents and expanded the applicability of complex inhibition mechanisms.

2. Microbiological tests performed in Postgate B nutrient medium revealed that the studied inhibitor compositions (at the optimal concentration of 7.0 mg/L) reduced the biogenic H_2S concentration from 270 mg/L to 18–25 mg/L. These findings confirm that the formulations significantly suppress the activity of sulfate-reducing bacteria (SRB), *Desulfovibrio* and *Desulfomicrobium*, and effectively

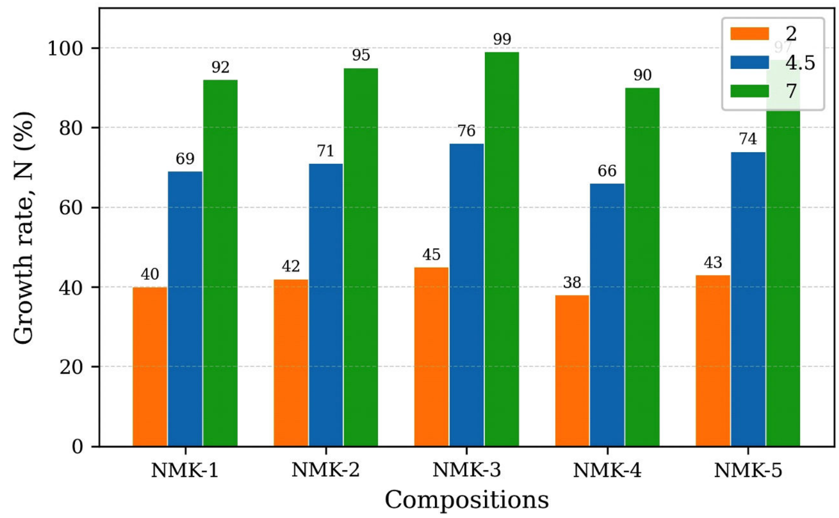

Fig. 5. Effect of NMK compositions on the growth rate N (%) of *Desulfomicrobium* (C_{NMK}=2, 4.5, 7 mg/L)

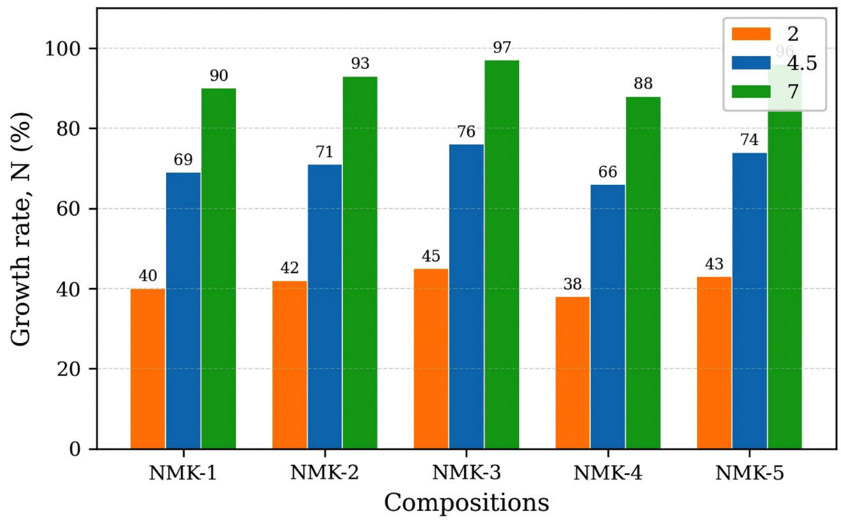

Fig. 6. Effect of NMK compositions on the growth rate N (%) of *Desulfovibrio desulfuricans* (C_{NMK}=2, 4.5, 7 mg/L)

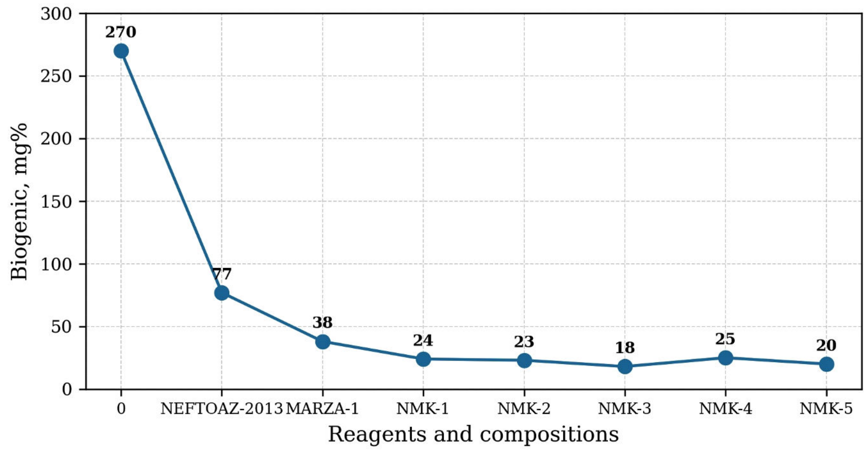

Fig. 7. Variation of biogenic H_2S concentration under the influence of individual reagents and NMK composite formulations

control the risk of microbiologically influenced corrosion (MIC).

3. Comparative gravimetric and microbiological analyses established that the NMK-3 composition (1:19 ratio) provides the most balanced and stable protection against both electrochemical and microbiological corrosion, owing to its optimal inhibitor distribution. The use of such composite systems represents a promising scientific direction for developing and implementing high-efficiency corrosion control strategies in industrial applications.

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РОЗРОБКА ТА ОЦІНЮВАННЯ ЕФЕКТИВНОСТІ СИНЕРГЕТИЧНОГО КОМПОЗИЦІЙНОГО ІНГІБІТОРА ПРОТИ ЕЛЕКТРОХІМІЧНОЇ ТА МІКРОБІОЛОГІЧНО ІНДУКОВАНОЇ КОРОЗІЇ

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Це дослідження присвячене оцінюванню захисної ефективності новорозробленої композиційної інгібіторної системи в умовах комплексної корозії за участю сульфатвідновлювальних бактерій (SRB) та електрохімічно активних компонентів. Основною метою було створення синергетичних композиційних інгібіторів, що забезпечують високу ефективність захисту за низьких концентрацій. Серед індивідуальних реагентів, що випробовувалися, «Neftqaz-2013» продемонстрував 90% ефективність захисту від корозії в електрохімічному середовищі за концентрації 1,0 мг/л, однак його активність була обмеженою в мікробіологічних умовах. Зокрема, швидкість росту штамів SRB родів Desulfovibrio та Desulfomicrobium досягала 78% і 80%, відповідно, тоді як концентрація біогенного сірководню зменшувалася лише до 77 мг/л. Натомість реагент «MARZA-1» виявив відносно слабку бактерицидну дію щодо SRB; навіть за максимальної дози показники росту залишалися в межах 82–84%, а рівень H_2S знижувався до 38 мг/л. Для подолання цих обмежень обидва реагенти було поєднано в різних співвідношеннях з метою одержання серії композицій типу NMK. Серед них композиція NMK-3 (співвідношення 1:19) забезпечила найкращі показники, гарантуючи 98% захисту від корозії в електрохімічному середовищі та 99% і 97% інгібування штамів Desulfovibrio desulfuricans і Desulfomicrobium, відповідно, за концентрації 7,0 мг/л. За цих умов концентрація біогенного H_2S зменшувалася до 18 мг/л. Гравіметричні та мікробіологічні дослідження проводилися відповідно до стандартів ASTM G31, ГОСТ 9.913-90 та NACE TM0172. Отримані результати продемонстрували, що, на відміну від індивідуальних реагентів, синергетичні композиційні інгібіторні системи виявляють вищу ефективність проти як електрохімічної, так і мікробіологічної корозії, що свідчить про їхній значний потенціал для промислового застосування.

Ключові слова: корозія; інгібітор; мікробіологічно індукована корозія; електрохімічна корозія; сульфатвідновлювальні бактерії; синергетична композиція.

DEVELOPMENT AND PERFORMANCE EVALUATION OF A SYNERGISTIC COMPOSITE INHIBITOR AGAINST ELECTROCHEMICAL AND MICROBIOLOGICALLY INFLUENCED CORROSION

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This study is devoted to evaluating the protective performance of a newly developed composite inhibitor system under complex corrosion conditions involving sulfate-reducing bacteria (SRB) and electrochemically active components. The main objective was to design synergistic composite inhibitors that provide high protection efficiency at low concentrations. Among the individual reagents tested, «Neftqaz-2013» exhibited 90% corrosion protection efficiency in an electrochemical environment at a concentration of 1.0 mg/L, but its activity was limited under microbiological conditions. Specifically, the growth rates of Desulfovibrio and Desulfomicrobium SRB strains reached 78% and 80%, respectively, while the concentration of biogenic hydrogen sulfide decreased only to 77 mg/L. Conversely, the «MARZA-1» reagent showed relatively weak bactericidal action against SRB; even at the highest dosage, the growth rates remained within 82–84%, and the H_2S level decreased to 38 mg/L. To overcome these limitations, both reagents were combined in different ratios to obtain a series of complex NMK-type compositions. Among them, the NMK-3 composition (1:19 ratio) provided the best performance, ensuring 98% corrosion protection in an electrochemical medium and 99% and 97% inhibition of Desulfovibrio desulfuricans and Desulfomicrobium strains, respectively, at a concentration of 7.0 mg/L. Under these conditions, the biogenic H_2S concentration was reduced to 18 mg/L. Gravimetric and microbiological analyses were conducted in accordance with ASTM G31, GOST 9.913-90, and NACE TM0172 standards. The results demonstrated that, unlike individual reagents, synergistic composite inhibitor systems exhibit superior performance against both electrochemical and microbiological corrosion, indicating their strong potential for industrial application.

Keywords: corrosion; inhibitor; microbiologically influenced corrosion; electrochemical corrosion; sulfate-reducing bacteria; synergistic composite.

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