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SYNTHESIS OF METAL CORROSION INHIBITORS BASED ON AMMONIA

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Abstract. This article presents a detailed study of the methods for the synthesis and application of ammonia-containing compounds as effective corrosion inhibitors for metals. For the synthesis of ammonia-based inhibitors, the reaction of ammonia with various aldehydes was investigated, which made it possible to establish the influence of the structure of the initial aldehydes on the anticorrosion properties of the resulting products. Particular attention is given to the development of a method for the interaction of ammonia with higher aldehydes in the presence of lower aldehydes, which promote the formation of highly reactive intermediate species. This approach ensures that the reaction proceeds under milder conditions and leads to the formation of compounds with improved protective characteristics and high stability. As a result of the conducted studies, a series of aldimine compounds was synthesized, the structures of which were confirmed by elemental analysis and IR spectroscopy. It was established that the obtained compounds exhibit high inhibition efficiency in acidic media, as confirmed by gravimetric and electrochemical studies. It was shown that the inhibition efficiency

depends on the molecular structure of the compounds, the length of the hydrocarbon chain, the presence of functional groups, as well as the conditions of their application. The use of the synthesized compounds contributes to an increase in the corrosion resistance of structural materials, an extension of the service life of equipment, and a significant reduction in operating costs. Ammonia and its derivatives are considered a promising and economically justified basis for the development of modern corrosion inhibitors capable of effectively regulating the acid–base balance of the medium and forming stable protective films. The obtained results can be used in the development of new complex inhibitor systems, including those based on petrochemical industry by-products, thereby ensuring both economic efficiency and environmental sustainability.

Keywords: corrosion inhibitors, ammonia, electrode processes, protective films, steel corrosion, inhibition mechanism

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АММИАК НЕГІЗІНДЕ МЕТАЛДАР КОРРОЗИЯСЫНЫҢ ИНГИБИТОРЛАРЫН СИНТЕЗДЕУ

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Аннотация. Берілген мақалада аммиакқұрамды қосылыстарды металдардың коррозиясына қарсы тиімді ингибиторлар ретінде алу және қолдану әдістері жан-жақты, жүйелі түрде қарастырылады. Аммиак негізіндегі ингибиторларды синтездеу үшін аммиактың әртүрлі альдегидтермен реакциясы зерттеліп, бастапқы альдегидтердің құрылысының алынатын өнімдердің коррозияға қарсы

қасиеттеріне әсері анықталды. Ерекше назар аммиактың жоғары альдегидтермен төменгі альдегидтердің қатысуымен әрекеттесу әдісін әзірлеуге аударылды, бұл реакцияға қабілетті аралық қосылыстардың түзілуіне ықпал етеді. Бұл өз кезегінде реакцияның жұмсақ жағдайда, энергия үнемдей отырып жүруін қамтамасыз етіп, қорғаныш қасиеттері жақсартылған әрі жоғары тұрақтылыққа ие қосылыстар алуға мүмкіндік береді. Жүргізілген зерттеулер нәтижесінде құрылымы элементтік талдау және ИҚ-спектроскопия әдістерімен расталған альдиминді қосылыстар қатары синтезделді. Алынған қосылыстардың қышқыл ортада жоғары ингибирлеуші белсенділік көрсететіні гравиметриялық және электрохимиялық зерттеулер нәтижелерімен толық дәлелденді. Ингибирлеу тиімділігі қосылыстардың молекулалық құрылысына, көмірсутек радикалының ұзындығына, функционалдық топтардың болуына, сондай-ақ қолдану жағдайларына және ортаның параметрлеріне тәуелді екені көрсетілді. Синтезделген қосылыстарды қолдану конструкциялық материалдардың коррозияға төзімділігін арттыруға, жабдықтардың қызмет ету мерзімін ұзартуға және пайдалану шығындарын едәуір төмендетуге ықпал етеді. Аммиак және оның туындылары ортаның қышқыл-сілтілік тепе-теңдігін тиімді реттей алатын және тұрақты қорғаныш қабықшалар түзетін заманауи коррозия ингибиторларын жасаудың болашағы зор әрі экономикалық тұрғыдан негізделген ғылыми-технологиялық негізі ретінде қарастырылады. Алынған нәтижелер жаңа кешенді ингибиторлық жүйелерді әзірлеуде, соның ішінде мұнай-химия өнеркәсібі қалдықтары негізінде қолданылуы мүмкін, бұл ұсынылған тәсілдердің экономикалық тиімділігі мен экологиялық орындылығын қамтамасыз етеді және өнеркәсіптік практикада кеңінен енгізілуіне мүмкіндік береді.

Түйін сөздер: коррозия ингибиторлары, аммиак, электродтық үдерістер, қорғаныш қабықшалар, болат коррозиясы, ингибирлеу механизмі

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СИНТЕЗ ИНГИБИТОРОВ КОРРОЗИИ МЕТАЛЛОВ НА ОСНОВЕ АММИАКА

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Аннотация. В данной статье рассматриваются методы получения и применения аммиаксодержащих соединений в качестве эффективных ингибиторов коррозии металлов. Для синтеза аммиачных ингибиторов исследована реакция аммиака с различными альдегидами, что позволило установить влияние структуры исходных альдегидов на антикоррозионные свойства получаемых продуктов. Особое внимание уделено разработке метода взаимодействия аммиака с высшими альдегидами в присутствии низших альдегидов, способствующих образованию реакционноспособных промежуточных соединений. Это обеспечивает протекание реакции в более мягких условиях и получение соединений с улучшенными защитными характеристиками и высокой стабильностью. В результате проведённых исследований синтезирован ряд альдиминовых соединений, структура которых подтверждена методами элементного анализа и ИК-спектроскопии. Установлено, что полученные соединения обладают высокой ингибирующей активностью в кислых средах, что подтверждается результатами гравиметрических и электрохимических исследований. Показано, что эффективность ингибирования зависит от молекулярной структуры соединений, длины углеводородного радикала, наличия функциональных групп, а также условий их применения. Применение синтезированных соединений способствует повышению коррозионной стойкости конструкционных материалов, увеличению срока службы оборудования и снижению эксплуатационных затрат. Аммиак и его производные рассматриваются как перспективная и экономически обоснованная основа для создания современных ингибиторов коррозии, способных эффективно регулировать кислотно-щелочной баланс среды и формировать устойчивые защитные плёнки. Полученные результаты могут быть использованы при разработке новых комплексных ингибиторных систем, в том числе на основе отходов нефтехимической промышленности, что повышает их экономическую эффективность и экологическую целесообразность.

Ключевые слова: ингибиторы коррозии, аммиак, электродные процессы, защитные плёнки, коррозия стали, механизм ингибирования

Introduction. Metal corrosion is one of the most significant problems limiting the durability and reliability of structural materials in industry. Each year, a substantial portion of resources is expended on repair, equipment replacement, and the prevention of damage to metal products. One of the most effective and technologically accessible protection methods is the use of corrosion inhibitors—chemical compounds that, when introduced into the operating environment, reduce the rate of electrochemical processes responsible for metal degradation. Interest in ammonia-based inhibitors arises from the fact that ammonia molecules and ammonium derivatives exhibit a pronounced ability to coordinate with metal surfaces, form stable adsorption layers, and modify the pH of

the medium. Ammonia is an inexpensive and readily available reagent, which makes it a promising component of protective formulations.

Literary review. Research in the field of corrosion inhibition using ammonia and its derivatives has been conducted for several decades. In a series of studies, I.D. Vdovenko and co-workers (Vdovenko et al., 1981; Valdez et al., 2018; Ansari et al., 2018) consistently developed the concept of the important role played by the formation of associates of solvent molecules, anions, and quaternary ammonium salts in the manifestation of their inhibiting properties. I.L. Rosenfeld and co-workers developed (Rozenfel'd et al., 1977; Dinodi et al., 2014; Liu et al., 2017) a series of universal volatile inhibitors known collectively as IFKhAN. These inhibitors are derivatives of low-molecular-weight amines and contain two heteroatoms—oxygen and nitrogen—in their molecular structure. E.S. Ivanov and V.P. Timonin (Ivanov, Timonin et al., 1988; Altsybeeva et al., 2014), as well as Ya.G. Avdeev and Yu.I. Kuznetsov (Avdeev et al., 2010; Cao et al., 2020), note a significantly higher inhibiting efficiency of aldehydes.

It has been established that benzaldehyde and its derivatives already exhibit sufficiently high inhibiting properties; according to reported data, aldehydes may undergo various chemical transformations leading to the formation of products with significant protective characteristics.

Recent studies by D. Puzikova and G.M. Khusurov (Puzikova et al., 2025; Kuznetsov et al., 2016) are focused on the synthesis of organic compounds containing amino groups capable of interacting with ammonia or acting as its functional analogues. It has been shown that such molecules are able to form compact adsorption films of a mixed physicochemical nature. Particular attention is paid to ammonium derivatives, quaternary ammonium salts, and ammonia complexes with transition metals.

The works of L.M. Kurbanov (Kurbanov et al., 2023) and M.A. Yusupov (Yusupov et al., 2025; Ojo et al., 2018) demonstrate that the efficiency of ammonia-based inhibitors is enhanced by the introduction of additional donor–acceptor centers into the system (e.g., oxygen-, nitrogen-, and sulfur-containing groups), as well as by combining ammonia with phosphates, carbonates, and surfactants. The authors note the strong influence of the medium pH, temperature, and electrolyte composition on the inhibition mechanism.

In Kazakhstan, the demand for corrosion inhibitors is very high and is fully met by imports, since there is no domestic production of metal corrosion inhibitors in the republic. Therefore, research aimed at the synthesis of metal corrosion inhibitors based on inexpensive domestic raw materials represents a highly important task. Particularly promising in this regard is the utilization of readily available large-scale wastes from petrochemical industries.

As is well known, the products of condensation reactions between ammonia or amines and aldehydes have found industrial application as highly effective metal corrosion inhibitors. For example, the condensation product of ammonia with formaldehyde—hexamethylenetetramine (urotropine)—is used as an inhibitor of acid corrosion of metals. However, its application is limited due to its relatively low efficiency, which is evidently associated with the absence of a hydrophobic moiety in the urotropine molecule. To overcome this drawback, various primary amines are widely used instead

of ammonia in condensation reactions with aldehydes. Nevertheless, these amines are expensive products. Therefore, an alternative approach appears to be of considerable interest, namely, the synthesis of metal corrosion inhibitors via the condensation of ammonia with other aldehydes in which the aldehyde group is bonded to aliphatic chains or aromatic radicals.

Materials and methods. The tests were carried out in a 5% H_2SO_4 solution for 24 hours at room temperature (20–25 °C) with an inhibitor concentration of 2 g/L. The inhibiting efficiency of the compounds was evaluated under static conditions using the gravimetric method on grade 3 steel.

The average corrosion rate ν_{avg} ($g \cdot m^{-2} \cdot day^{-1}$) was determined based on the mass loss of steel coupons and calculated using the formula:

$$\nu_{avg} = \frac{m_1 - m_2}{S \cdot \tau}$$

where m_1 is the mass of the steel coupon before the experiment (g);
m_2 is the mass of the steel coupon after the experiment (g);
S is the surface area of the sample (m^2);
τ is the exposure time (days).

The protective efficiency of the inhibitor (Z, %) was calculated using the following equation:

$$Z = \frac{C_0 - C_i}{C_0} \times 100$$

where C_0 is the corrosion rate of the metal in the absence of the inhibitor ($g \cdot m^{-2} \cdot day^{-1}$);
C_i is the corrosion rate of the metal in the presence of the inhibitor ($g \cdot m^{-2} \cdot day^{-1}$).

The corrosion penetration rate ($\mu m \cdot year^{-1}$) was calculated by the formula:

$$\mu = \frac{\nu_{avg} \cdot 1000}{\rho} \cdot 24 \cdot 365$$

where ν_{avg} is the average corrosion rate ($g \cdot m^{-2} \cdot h^{-1}$);
ρ is the density of the metal, ($g \cdot cm^{-3}$) (ρ(Fe) = 7,87 $g \cdot cm^{-3}$);
1000 is the conversion factor from mm to μm.

The corrosion tests were conducted in 5% H_2SO_4 at room temperature for 24 hours using a 2 g/L inhibitor concentration on grade 3 steel. The average corrosion rate, inhibitor efficiency, and corrosion penetration rate were calculated based on mass loss measurements, allowing quantitative evaluation of the protective effect of the synthesized compounds. These methods provided reliable data for comparing the anticorrosion performance of different inhibitors under controlled static conditions.

The experimental data demonstrated that an increase in inhibitor concentration leads to a consistent decrease in the corrosion rate of steel. At low concentrations (0.5–1.0 g/L), the protective effect is limited, which is associated with incomplete coverage of the metal surface by the adsorbed inhibitor layer. In this case, active surface sites remain accessible for anodic and cathodic reactions.

As the concentration increases to 2.0–3.0 g/L, a significant improvement in inhibition efficiency is observed, which can be attributed to the formation of a denser and more uniform protective film. It is likely that, within this concentration range, the system approaches a state close to surface saturation by adsorbed inhibitor molecules. A further increase in concentration to 4.0–5.0 g/L results in only a slight enhancement of the protective effect, indicating the attainment of maximum adsorption and the formation of a quasi-monolayer.

Analysis of adsorption isotherms suggests that the adsorption of inhibitors on the steel surface follows the Langmuir model, indicating a predominantly monomolecular nature of the surface coverage and the absence of significant interactions between the adsorbed species. At the same time, the presence of donor–acceptor centers (nitrogen and oxygen atoms) in the inhibitor molecules promotes the formation of coordination bonds with the metal surface, thereby enhancing the contribution of chemisorption.

The effect of temperature on inhibition efficiency was investigated in the range of 20–60° C at a fixed inhibitor concentration of 2 g/L. It was found that an increase in temperature leads to an acceleration of the corrosion rate both in the absence and in the presence of the inhibitor, which is associated with the intensification of electrochemical reactions and diffusion processes in the solution. However, the inhibition efficiency (Z%) shows a non-linear dependence on temperature.

At a moderate temperature increase up to 40°C, a slight decrease in the protective effect is observed, which may be attributed to partial desorption of inhibitor molecules from the metal surface. Nevertheless, the relatively high level of protection indicates a significant contribution of chemical adsorption. With a further increase in temperature up to 60°C, the inhibition efficiency decreases more substantially, suggesting disruption of the integrity of the protective film and an intensification of metal dissolution processes.

The calculation of the activation energy of the corrosion process showed that its value increases in the presence of the inhibitor compared to the uninhibited system. This indicates an increase in the energy barrier of the corrosion process and confirms the effectiveness of the studied compounds as mixed-type inhibitors.

Thus, it has been established that maximum inhibition efficiency is achieved at concentrations of 2.0–3.0 g/L and moderate temperatures. The obtained results indicate that the protective mechanism of the synthesized compounds is governed by a combination of physical and chemical adsorption, as well as the formation of stable protective films on the steel surface. Consideration of the effects of concentration and temperature is an important factor in the development and optimization of inhibitor formulations for practical application in aggressive environments.

Results. It could be expected that nitrogenous bases synthesized via the condensation reaction of ammonia with higher aldehydes would exhibit high anticorrosion activity.

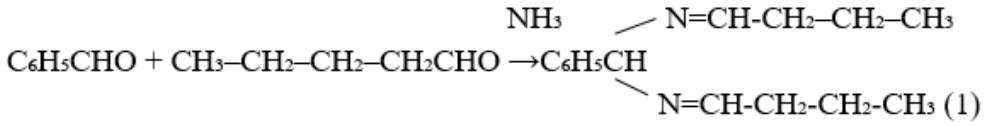
Furthermore, higher aliphatic aldehydes are produced in large quantities as waste in the petrochemical industry.

However, higher aldehydes do not react with ammonia under standard conditions, whereas lower aldehydes are known to react readily with ammonia, forming intermediate geminal hydroxyamines. From the above, it follows that geminal hydroxyamines formed during the initial stage of the reaction of ammonia with lower aldehydes cannot be isolated, as they undergo further reaction with each other, yielding more complex compounds. Based on this fact, we hypothesized that higher aldehydes could react with ammonia if lower aldehydes were added to the mixture, as these form highly reactive intermediate hydroxyamines. In these geminal hydroxyamines, the nitrogen atom exhibits increased nucleophilicity due to the α-effect.

The following condensation reactions of ammonia with aldehydes were carried out and studied:

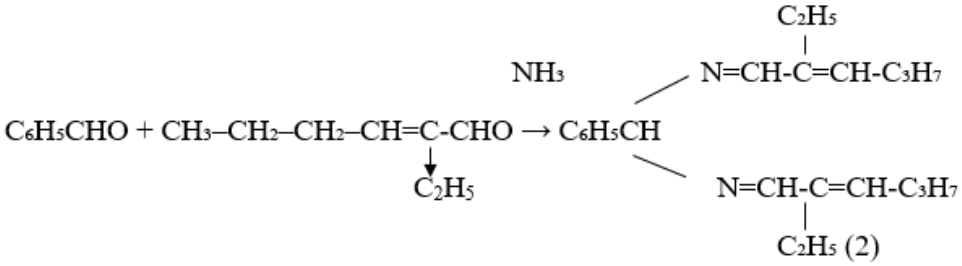
1. Reaction of ammonia with butyraldehyde in the presence of benzaldehyde;
2. Reaction of ammonia with 2-ethylhexenal-2-1 in the presence of benzaldehyde;
3. Reaction of ammonia with 2-ethylhexenal-2-1 in the presence of butyraldehyde;
4. Reaction of ammonia with 2-ethylhexenal-2-1 in the presence of formic acid.

1.Reaction of Ammonia with Butyraldehyde in the Presence of Benzaldehyde. Ammonia was passed through a mixture of butyraldehyde and benzaldehyde in a molar ratio of 2:1. Upon completion of the exothermic reaction, the reaction mixture was distilled under reduced pressure, yielding the product as a viscous liquid, benzald[butyraldimine] (1):



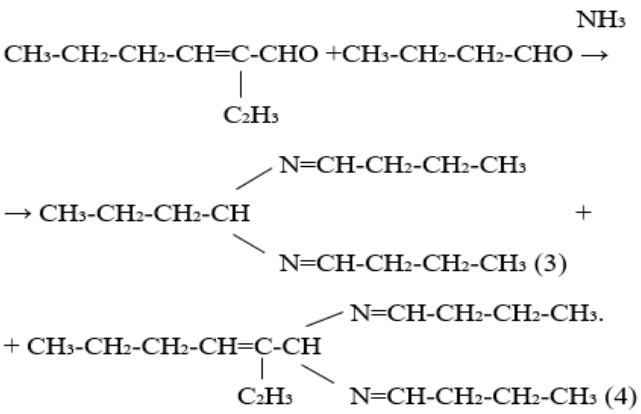
The structure and composition of the obtained compound (1) were confirmed by elemental analysis and IR spectroscopy. The IR spectrum of benzald[butyraldimine] (1) exhibits absorption bands at 1641, 1664, and 1688 cm^{-1}, characteristic of the azomethine group vibrations (Ar–CH=N–R). Bands in the regions 2800–3000, 1300–1400, and around 700 cm^{-1} correspond to characteristic C–H vibrations of methyl, methylene, and methine groups. Additionally, absorption bands at 1500, 1600, and 1465 cm^{-1} are indicative of the benzene ring.

2.Reaction of Ammonia with 2-Ethylhexenal-2-1 in the Presence of Benzaldehyde. Gaseous ammonia was passed through 2-ethylhexenal-2-1, a by-product of 2-ethylhexanol production, at room temperature, while benzaldehyde was gradually added. A slight warming of the reaction mixture was observed during the process. After approximately thirty minutes, the exothermic reaction was complete, and the supply of gaseous ammonia was stopped. A solid precipitate was formed, which was separated from the unreacted liquid products:



The compound benzald[2-ethylhexenalimine] (2) was obtained, and its structure and composition were confirmed by elemental analysis and IR spectroscopy. The IR spectrum exhibits absorption bands at 1500 and 1600 cm^{-1}, characteristic of the benzene ring, bands at 1640–1680 cm^{-1}, corresponding to azomethine groups (Ar–CH=N–R), and bands at 2800–3000, 1300–1400, and around 700 cm^{-1}, which are characteristic of methyl, methylene, and methine groups.

3. Reaction of Ammonia with 2-Ethylhexenal-2-1 in the Presence of Butyraldehyde. Gaseous ammonia was passed through a mixture of butyraldehyde and 2-ethylhexenal-2-1 in a molar ratio of 1:1. Upon completion of the exothermic reaction, the reaction mixture was distilled under reduced pressure. Two products were obtained: N-butylenedi[butyraldimine] (3) and 2-ethylhexen-2-di[butyraldimine] (4):

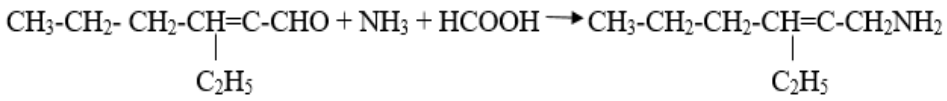


The composition and structure of both compounds were confirmed by IR spectroscopy and elemental analysis. The IR spectrum of N-butylenedi[butyraldimine] (3) exhibits absorption bands characteristic of azomethine groups at 1642, 1665, and 1690 cm^{-1} (R–CH=N–R') and bands corresponding to methyl and methylene groups at 2850, 2890, 1380, and 700 cm^{-1}.

The IR spectrum of 2-ethylhexen-2-di[butyraldimine] (4) shows absorption bands at 1639, 1643, 1683, and 1689 cm^{-1}, attributable to azomethine groups (R–CH=N–R'), and bands corresponding to methyl and methylene groups at 2882, 2960, 1378, and 700 cm^{-1}.

In this case, the main product of the reaction is compound (3), while the yield of compound (4) is relatively low, which can be attributed to steric factors.

4.Reaction of Ammonia with 2-Ethylhexenal-2-1 in the Presence of Formic Acid. When ammonia reacts with aldehydes in the presence of formic acid, mixtures of primary, secondary, and tertiary amines are formed (Leuckart–Wallach reaction). It is known that the yield of specific amines depends on the molar ratio of the starting reagents. The higher the proportion of ammonia and formic acid relative to the aldehyde, the greater the yield of the primary amine. In the reaction of 2-ethylhexenal-2-1 with ammonia and formic acid, the latter were used in fourfold excess relative to the aldehyde, and the reaction was carried out at a temperature of 160 °C.



The yield of the primary amine (5) was 61% of the theoretical value. The structure and composition of the synthesized 2-ethylhexyl-2-amine (5) were confirmed by elemental analysis and IR spectroscopy. The IR spectrum of the amine exhibits absorption bands at 3329 and 3242 cm^{-1}, corresponding to the amino group (–NH_2), and a broad band at 720 cm^{-1}, characteristic of primary amines. Absorption at 1158 cm^{-1} is attributed to the C–N bond, while bands at 2863, 2915, 1381, and 1464 cm^{-1} correspond to vibrations of methyl and methylene groups. A broad band at 1610–1648 cm^{-1} is assigned to the deformation vibrations of the amino group, which overlaps with the stretching vibrations of the double bond, whose C–H stretching vibrations appear at 3025 cm^{-1}.

These compounds were tested as metal corrosion inhibitors. The study demonstrated that the protective efficiency of the hydroxyamine derivatives follows the order of decreasing activity as follows:2-ethylhexen-2-di[butyraldimine] – 98.5%, benzald[2-ethylhexen-2-aldimine] – 96.01%, N-butylenedi[butyraldimine] – 88.39%, benzald[butyraldimine] – 84.21% (Table 1).

Table 1 - Results of the Testing of Products from the Reaction of Ammonia with Aldehydes.

№	Inhibitors	C_0, $g \cdot m^{-2} \cdot h^{-1}$	$C_к$, $g \cdot m^{-2} \cdot h^{-1}$	Z, %	$К_п$
1	Benzald[butyraldimine]	11,15	1,76	84,21	6,33
2	Benzald[2-ethylhexen-2-aldimine]	10,79	0,43	96,01	25,09
3	N-Butylenedi[butyraldimine]	12,06	1,40	88,39	8,61
4	2-Ethylhexen-2-di[butyraldimine]	10,64	0,15	98,59	70,93

To further elucidate the inhibition mechanism of the synthesized compounds, additional electrochemical studies were performed, including potentiodynamic polarization and electrochemical impedance spectroscopy techniques.

The results of potentiodynamic measurements demonstrated that, in the presence of the investigated inhibitors, both anodic and cathodic polarization curves shift toward

lower current densities. At the same time, no significant shift in the corrosion potential was observed (not exceeding ±85 mV), indicating that the synthesized compounds act as mixed-type inhibitors, simultaneously suppressing the anodic metal dissolution process and the cathodic hydrogen evolution reaction.

The decrease in corrosion current density in the presence of the inhibitors correlates well with the results of gravimetric measurements. The most pronounced reduction in corrosion current density was observed for compound 2-ethylhexene-2-di[butyraldimine] (4), confirming its highest inhibition efficiency (up to 98.59%). These findings suggest that an increase in the hydrocarbon chain length and the presence of multiple bonds enhance adsorption and promote the formation of a more stable protective film.

Discussions. The electrochemical impedance spectroscopy data also confirm the effectiveness of the inhibitors. Nyquist plots reveal an increase in the diameter of the capacitive semicircle in the presence of inhibitors, indicating an increase in charge transfer resistance. The increase in reflects a slowdown of electrochemical reactions at the metal–solution interface. Simultaneously, a decrease in the double-layer capacitance is observed, which is associated with the displacement of water molecules and ions from the metal surface and their replacement by adsorbed inhibitor molecules.

The reduction in double-layer capacitance can be interpreted as a result of an increase in the thickness of the protective layer and a decrease in the dielectric constant of the near-surface region. This confirms the formation of a dense adsorbed film with barrier properties.

Based on the combined gravimetric and electrochemical data, the following inhibition mechanism can be proposed. Molecules of the synthesized azomethine compounds and amines are adsorbed on the steel surface through donor–acceptor interactions between the lone electron pairs of nitrogen atoms and the vacant d-orbitals of iron atoms. Additional contribution to adsorption arises from the π-electrons of the azomethine group (–CH=N–) and aromatic fragments (in the case of benzaldehyde derivatives).

Hydrophobic alkyl chains are oriented away from the metal surface toward the solution, forming a barrier layer that impedes the diffusion of aggressive ions (H^+, SO_4^{2-}) to the metal surface. As a result, a combined protective film is formed, incorporating both physical and chemical adsorption components.

Thus, the inhibition mechanism of the synthesized compounds is governed by adsorption on active surface sites, blocking of anodic and cathodic reactions, formation of a dense hydrophobic protective film, an increase in charge transfer resistance, and a decrease in double-layer capacitance.

The obtained electrochemical data are in good agreement with the gravimetric results and confirm the high efficiency of the synthesized ammonia-based compounds as corrosion inhibitors for steel in acidic media.

Experimental studies demonstrated that the synthesized ammonia-containing compounds exhibit high corrosion inhibition efficiency for steel in acidic media, comparable to, and in some cases exceeding, the performance of commercially used inhibitors. The maximum protective activity of 2-ethylhexen-2-di[butyraldimin] reaches 98.59 %, which is significantly higher than the efficiency of conventional organic

inhibitors such as amines and amino acids, whose performance typically ranges from 70–90 % under similar conditions.

A comparison with industrial products highlights the following advantages of the synthesized compounds:

- High inhibitory activity at moderate concentrations – the optimal range is 2–3 g/L, within which a dense and uniform protective film is formed. While comparable to industrial inhibitors, the synthesized hydroxylamines provide a higher protection coefficient (up to 70.93 for Kp), reflecting more complete blocking of both anodic and cathodic processes.

- Temperature stability – inhibition efficiency is maintained at moderate temperature increases up to 40°C, with partial loss at 60°C. Many commercially applied inhibitors lose protection more rapidly due to weak adsorption and desorption from the metal surface.

- Mechanism of action – a combination of physical and chemical adsorption, formation of coordination bonds via donor-acceptor centers, and π-electrons of the azomethine group. Industrial inhibitors often rely primarily on physical adsorption or limited chemical interaction, which reduces the durability of the protective layer.

- Structural flexibility and feedstock availability – using both higher and lower aldehydes, including petrochemical by-products, allows the synthesis of compounds with varied hydrocarbon chain lengths and functional groups. This enables "fine-tuning" of properties, which is difficult to achieve with industrial inhibitors.

- Economic and environmental advantages – the synthesized compounds can be obtained from readily available, including secondary, raw materials, reducing cost and increasing environmental feasibility compared to industrial inhibitors based on expensive amines or aromatic compounds.

Consequently, the synthesized ammonia-containing hydroxylamines demonstrate high potential as effective, economical, and environmentally justified alternatives to industrial corrosion inhibitors, combining high protective activity, temperature resilience, structural adaptability, and raw material accessibility. Their use enables the formation of more stable protective films, extends equipment service life, and reduces operational costs.

Conclusion. Thus, as a result of the conducted studies, a new method for the condensation of higher aldehydes with ammonia in the presence of more reactive lower aldehydes was developed and experimentally validated. The proposed approach allows for increased reaction efficiency, milder synthesis conditions, and an expanded raw material base through the use of readily available aldehydes of various structures. This provides a foundation for scaling up the process and implementing it in practical organic synthesis.

It was established that the hydroxyamines synthesized during the reactions exhibit pronounced inhibiting properties. Corrosion tests demonstrated that the protective efficiency of the investigated compounds varies over a wide range, from 84.21% to 98.59%, indicating that the inhibitory effect depends on the chemical nature of the compounds, their concentration, and the conditions of application. The high levels

of protective efficiency suggest that the obtained hydroxyamines can be considered promising components of inhibitor formulations.

The practical significance of these results lies in the potential application of the synthesized hydroxyamines as effective corrosion inhibitors in various industrial sectors, including oil and gas, chemical, and metallurgical industries. The use of these compounds can contribute to extended service life of metallic equipment, reduced operational costs, and improved reliability of technological systems. Additionally, the results open avenues for further optimization of inhibitor structures and the development of new protective materials based on these hydroxyamines.

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