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Carbon dioxide corrosion inhibitors: current state of research and development

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Abstract
Among the methods of corrosion control in the oil and gas production industry the leading place belongs to inhibitor protection, since there is no need for technological and technical changes in the existing equipment. The combination of high variability of inhibitor composition with changing conditions of its application and low capital investments makes it an indispensable reagent at oil and gas fields. The main classes of compounds used as active bases of carbonic acid corrosion inhibitors for the protection of oil and gas equipment are described. Classical organic active bases containing heteroatoms (oxygen, sulfur, nitrogen) are examined. Special attention was paid to alkylimidazolines and other nitrogen-containing compounds as the most frequently used as active bases of carbonic acid corrosion inhibitors in Russia and abroad. A wide range of possibilities to achieve the desired properties of corrosion inhibitors by varying the substitutes has been demonstrated. Nowadays, in addition to the traditional requirements for corrosion inhibitors, their safety for the environment is equally important. The information on prospective research and development aimed at improving the environmental characteristics of the reagents used is given. Plant extracts, synthetic and biological polymers involved in traditional corrosion inhibitors or used as new independent compounds are considered. It is shown that the effectiveness of corrosion inhibitors significantly depends on the pH of the medium, temperature, partial pressure of CO_2, flow rate, and other factors.

Keywords
corrosion inhibitor; carbonic acid corrosion; imidazoline; CO_2; green inhibitors; plant inhibitors; polymeric inhibitors; synthetic polymers; biopolymers

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Introduction

Oil and gas industry equipment is subject to aggressive influence of the external environment. One of the main factors of accidents (up to 80 %) and failure of oilfield equipment is corrosion of external and internal pipe walls. When the metal surface is in contact with a medium (a mixture of liquid and gaseous hydrocarbons), the corrosion process is significantly accelerated in the presence of hydrogen sulfide, carbon dioxide, water, oxygen, and mechanical impurities [1].

Factors having maximum influence on the mechanism and intensity of corrosion of field oil and gas pipelines [2, 3]: high water content of transported products; high content of corrosive-aggressive gases (carbon dioxide and/or hydrogen sulfide); high temperature of transported products; high content of mechanical impurities.

Previously, carbon dioxide was not considered as an active corrosive agent; hydrogen sulfide and oxygen posed a significant threat. However, the situation has changed dramatically with the

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development of deep-lying seam. The simultaneous presence of bicarbonate and carbonate ions in the aqueous phase causes carbonic acid corrosion, which leads to failure of oil and gas field equipment. [4]. The simultaneous presence of bicarbonate and carbonate ions in the aqueous phase causes carbonic acid corrosion, which leads to failure of oil and gas field equipment [2]. At 25-35 % content of the water phase in the oil-water mixture, the surface of steel equipment is wetted by water, which causes corrosion stimulated by CO_2 dissolved in the mixture [5]. The rate of corrosion damage is 3-4 mm/year and in some cases reaches 6-8 mm/year. When predicting corrosion rates, it should be assumed that the carbon dioxide content in the aqueous phase is closely related to the partial pressure of carbon dioxide (pCO_2 > 0.2 MPa – severe corrosion, pCO_2 = 0.02-0.2 MPa – moderate, pCO_2 < 0.02 MPa – insignificant [6]), and the partial pressure is temperature dependent [7].

One solution to the environmental problem of carbon dioxide emission and decarbonization of the industrial sector is the use of carbon capture, utilization and storage (CCUS) technology. However, carbon dioxide corrosion is a serious problem that has hindered the widespread development and application of this technology [8, 9].

Three temperature areas can be distinguished in the carbon dioxide corrosion process [10]:

• low temperature area (below 60 °C) – corrosion is mostly uniform and its rate increases with increasing temperature; small amounts of $FeCO_3$ are formed on the metal surface;

• medium temperature area (about 100 °C) – the formed iron carbonate film is uneven in thickness; local corrosion intensifies, the rate of which reaches a maximum;

• high temperature area (above 150 °C) – corrosion rate decreases (by an order of magnitude or more) due to the formation of a dense coating of iron oxide (Fe_3O_4) with high adhesion.

Carbon dioxide can cause both uniform and more dangerous localized (moss-like and meso-like pitting) corrosion of steel. In the process of localized corrosion, an irregular and/or unstable protective film of corrosion products is formed on the metal surface ($FeCO_3$, Fe_3O_4, etc.).

Methods of corrosion control in the oil industry:

• technological methods of protection, i.e. creation and maintenance of corrosion-safe conditions of equipment operation;

• use of corrosion-resistant/non-metallic materials [11];

• application of corrosion inhibitors (CI);

• use of protective coatings.

Among the listed methods of corrosion control in the oil and gas production industry in Russia and abroad, the leading place is currently occupied by inhibitor protection, as it does not require significant capital investments and a serious restructuring of the technology of oil production, gathering and treatment [10]. CI are fast acting and cost effective, so no field containing aggressive components is operated without the use of corrosion inhibitor protection. The advantage of this method is its simplicity and cost-effectiveness, possibility to use it both on new and operated wells, which allows in the process of field development to easily replace the existing inhibitor with a more effective one without disturbing the production technology at the fields. In the Russian Federation, corrosion inhibitors are used during the development of oil and gas fields as prescribed by Gosgortechnadzor [2].

Inhibitors are supplied to pipeline systems with periodic or continuous dosing. During periodic dosing, contact of the pipeline metal surface with the commercial form of inhibitor or its concentrated solution is organized. At the same time, inhibitors should have an effect of after-action, i.e. the protective layer formed by their application should retain its integrity for a long time. At constant dosing the formation and maintenance of the protective layer is realized due to diffusion of the active

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component of the inhibitor from the liquid volume on the metal surface of the pipeline wall. The effectiveness of pipeline protection with corrosion inhibitors depends on the chemical composition, adsorption capacity and the amount of inhibitor injected [12-14].

Carbon dioxide corrosion inhibitors

Corrosion inhibitors are chemical compounds that reduce the rate of corrosion without significantly changing the concentration of any corrosion reagent. The ability of inhibitors to retard corrosion is mainly due to the following properties: adsorption of CI on the metal surface; change in the rate of anodic/cathodic reactions; slowing down the rate of CI diffusion to the metal surface; decrease in the electrical resistance of the metal surface.

The corrosion inhibitor acts at the metal/solution interface to form a film of various types – passivating, precipitating and adsorptive.

The most widespread use of passivators is for corrosion control in neutral or near-neutral pH environments. The chemical composition and structure of inhibitors largely determines their mechanism of action. Among inhibitors one can find inorganic substances with oxidizing properties (nitrites, molybdates, tungstate, chromates), which are able to create protective oxide films on the surface of the corroding metal. Currently, the use of inhibitors of this type has been abandoned due to toxicity; they are used only in the aviation industry and construction.

Precipitating film inhibitors are chemicals that form insoluble protective films by reacting with soluble substances in the environment (e.g., phosphonates and polyphosphates that form protective films with calcium ions in solution) or with the protected medium – metal ions (e.g., copper-benzotriazole salt film (BTA) [1].

Inhibitors that form adsorptive protective films are mainly organic substances (surfactants), which often have a surfactant molecular structure with a hydrophilic group capable of binding to the metal surface and a hydrophobic part of the molecule protruding towards the solution volume. The adsorbed inhibitor molecules restrict oxygen diffusion and water access to the metal surface, which reduces the corrosion rate.

Modern adsorption-type corrosion inhibitors are usually a solution of one or more organic compounds with high inhibitory properties (active base) in a hydrocarbon or water-alcohol solvent.

There are a number of requirements for corrosion inhibitors used in the oil industry:

• protective effect in a wide range of temperatures and pressures (from normal to high), as well as in conditions of high flow velocities and the presence of abrasive particles;

• low solidification temperature (not less than –50 °C);

• good solubility and/or dispersibility in working media (water-soluble, hydrocarbon-soluble, hydrocarbon-soluble-water-dispersible, insoluble in neither water nor hydrocarbons);

• absence of influence on the stability of oil-water emulsions;

• fire and explosion safety, compliance with the requirements of sanitary norms;

• compatibility with other reagents used in the technological process and absence of influence on the quality and processes of subsequent oil refining, etc.

Also, when developing effective corrosion inhibitors, it is worth considering the environmental impact, the possibility of use at low concentrations (100-200 mg/l), and chemical stability in corrosive environments.

All commercially available corrosion inhibitors have an optimal area of application depending on the industry segment, composition of corrosive media and technological features of the protected objects [15]. Table 1 shows the most common composition of corrosion inhibitors used in various fields.

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Table 1

Composition of inhibitors used in various segments of the oil and gas industry

Segment	Inhibitors	Composition	Medium
Oil field	Corrosion inhibitors	Linear amines and imidazolines in various solvents (kerosene, methanol, neonol, etc.)	Oil emulsion
Chemical-technological equipment protection	Corrosion inhibitors	Oxyethylated fatty amines and imidazolines	Petroleum products with various impurities
Water treatment	Complex inhibitors	Organophosphorus substances	Water
Water treatment of recycled industrial water enterprises	Complex inhibitors	Phosphorus-containing components, sodium polyphosphates. Zinc sulphates etc.	Water with various impurities

The main volume of reagents is used in the processes of production (for protection of pressure, oil gathering, in-field pipelines and water lines) and transportation of crude oil (Fig.1). Therefore, the most urgent is the development of new and improvement of currently used corrosion inhibitors, including carbon dioxide, used in the oil industry.

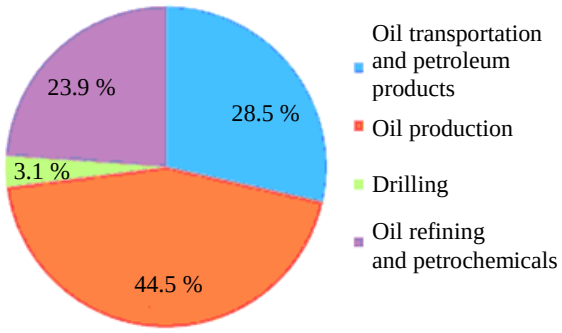
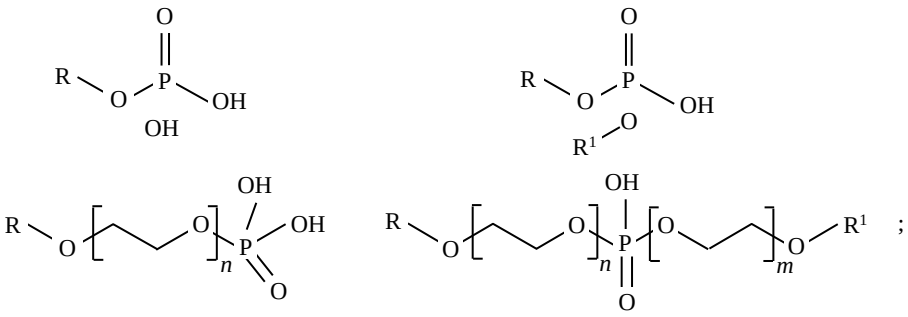


Fig.1. Use of corrosion inhibitors in various segments of the oil and gas industry

Organic corrosion inhibitors

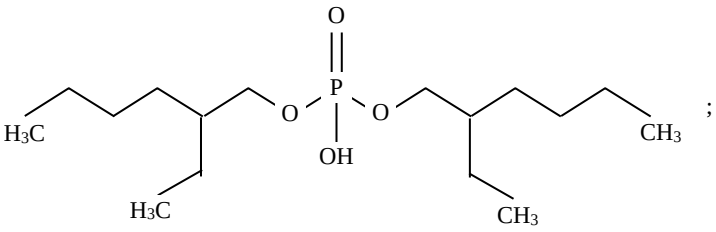
Organic compounds containing heteroatoms (O, P, N, S) are being actively studied as corrosion inhibitors [16, 17]. Structures of the main phosphorus-, oxygen- and sulfur-containing compounds used in industry as active bases of carbon dioxide corrosion inhibitors:

• esters of phosphoric acid [16]



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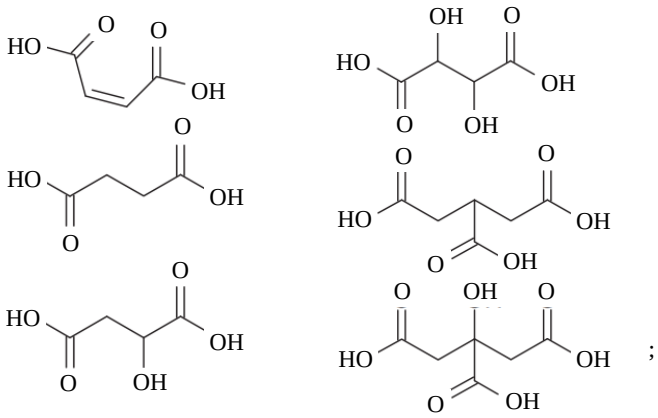
• bis(2-ethylhexyl) phosphate [18]



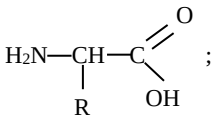
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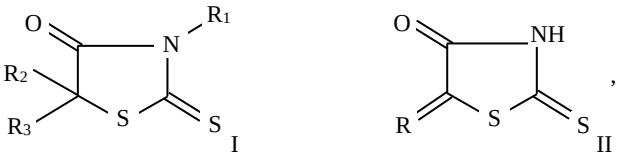
• carboxylic acids [19]



• amino acids and their derivatives [20]



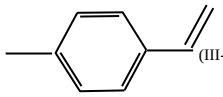
• rhodanine and derivatives [21]



where

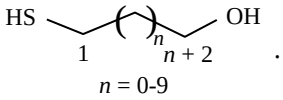
$R_1 = R_2 = R_3 = H_{(I\text{-}1)}R = (CH_3)_2C = {}_{(II\text{-}1)}R_1 = NH_2$;

$R_2 = R_3 = H_{(I\text{-}2)}R = H\text{–}C_5H_{11}CH =_{(II\text{-}2)} R_1 = CH_2CH = CH_2$;

$R_2 = R_3 = H_{(I\text{-}3)}R = (C_2H_5)_2N$  ${}_{(III\text{-}3)}R_1 = H - C_4H_9$;

$R_2 = R_3 = H_{(I\text{-}4)}R_1 = CH_4COOH$; $R_2 = R_3 = H_{(I\text{-}5)}R_1 = H$, $R_2 = H$, $R_3 = C_2H_{5\,(I\text{-}6)}$;

• ω-mercaptoalcohols [22]



Phosphorus-containing compounds

The mechanism of adsorption of inhibitor molecules on the metal surface can be considered as donor-acceptor: heteroatoms containing π-electrons act as donors, and free *d*-orbitals of metal surfaces act as acceptor [16]. This interaction leads to the formation of a protective layer on the metal surface. The ability of phosphorus atoms to form adsorption bonds at the expense of π-electrons and vacant *d*-orbitals of transition metals determines the chemisorption and inhibitory properties of phosphorus-containing compounds, which are used as corrosion inhibitors individually or in mixtures.

Mono- and diethers of phosphoric acid form sparingly soluble salts with ions Fe^{2+} and Ca^{2+}, which form a protective layer on the metal surface, thereby reducing the rate of corrosion.

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Corrosion inhibitors based on organic phosphorus compounds, such as N-heterocyclic alkylphosphonic acid $HtC(R_1R_2)P(O)(OH)_2$, where Ht – is a heterocyclic fragment with a nitrogen atom in the ring – pyrrolidine or morpholine, showed a high degree of protection against local corrosion; R_1, R_2 – are hydrogen atoms (alkyl radicals CH_3 or CH_3 and C_2H_5) [23]. The presence of the acid residue $P(O)(OH)_2$ in the molecule provides the formation of a nanoscale self-organizing layer on the metal surface at the inhibitor concentration in aqueous solution from 30 to 60 mg/l.

In the research [18] the possibility of using bis(2-ethylhexyl)phosphate to inhibit carbon dioxide corrosion is reported. It is shown that P–O–Fe and P–Fe bonds are formed on the metal surface, due to which the corrosion inhibitor shows high efficiency – 93 % at a concentration of 500 ppm.

Oxygen-containing compounds

Carboxylic acids show high protective ability (above 90 %) in conditions of carbonic acid corrosion [19], while the inhibition efficiency is primarily associated with adsorption of carbonyl groups –C=O on the metal surface and significantly increases with increasing their amount. Tricarboxylic acids exhibit maximum efficacy even at low inhibitor concentrations. The presence and number of hydroxyl groups in the structure of the inhibitor molecule has a significant effect on its efficiency – succinic and maleic acids, which have no hydroxyl groups in their composition, showed better inhibition efficiency than malic and tartaric acids.

Amino acids, particularly glutamic acid, are effective corrosion inhibitors, but the concentration should be carefully selected depending on the environmental conditions, as the opposite effect can be achieved [20]. Amino acids are environmentally friendly compounds that are completely soluble in aqueous media, non-toxic and cheap, so more and more research has been directed towards the synthesis of amino acids and their more complex derivatives to improve the effectiveness of corrosion inhibitors [24].

In the research [25], the esterification reaction of natural petroleum acids with allylic alcohol in the presence of an ionic liquid, N-methylpyrrolidone hydrosulfate, was studied. Based on of the obtained allyl alcohol of petroleum acid nitro derivatives were synthesized, their salts and complexes were obtained and the influence of solutions of these compounds on the kinetics of the corrosion process was investigated. The nature of salts and complexes was found to affect the effectiveness of CO_2 corrosion inhibitors and varies in a series: potassium salt > monoethanolamine complex > diethanolamine complex. Potassium salt and monoethanolamine complex based on nitro product of natural petroleum acids showed the highest anticorrosion efficiency at a concentration of 300 ppm, which amounted to 98.4 and 98.9 %, respectively.

Sulfur-containing compounds

The authors of the source [21] suggest the use of rhodanine and its 3- or 5-derivatives of general formula I or II as a corrosion inhibitor. It was found that inhibitors exhibit high protective properties (up to 99 %) in carbonic acid corrosion of iron at very low concentrations (0.1-2.5 mg/l).

Decantiol can be an effective inhibitor of localized corrosion in carbonate media due to the formation of adsorption monolayer [26] and reduction of adsorption/desorption processes of intermediate compounds on the metal surface resulting from the slowing down of cathodic and anodic reactions. It was found that the introduction of 10-400 ppm decanthiol can reduce the local corrosion of carbon steel. Investigations of the metal surface by physicochemical methods made it possible to establish that corrosion protection is provided by physical adsorption of the inhibitor on the metal surface rather than by chemisorption, since no Fe–S bonds were detected.

The relationship between the structure of a number of mercaptoalcohols and their anticorrosion efficacy as corrosion inhibitors was studied in [22]. While using molecular dynamic modeling, it was found that the high efficiency of mercaptoalcohols is due to their ability to adsorb on the Fe (110) surface with both –SH- and –OH-groups. As the carbon chain lengthens, the corrosion resistance properties improve and the optimum chain length is C_{11}.

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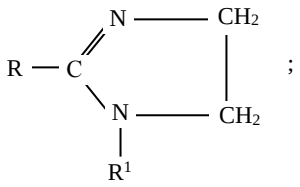
When straight, branched, cyclic or heterocyclic alkylene, arylene, alkylarylene, arylalkylene or hydrocarbon fragments containing from 1 to 30 carbon atoms of carbon-containing radicals with the general formula (HS)*n*–R–(OH)*m* (*n*, *m* = 1-3), are introduced into mercaptoalcohols, the anticorrosive efficiency increases [27]. The best reduction in both uniform and localized corrosion rates was achieved in the presence of 2-mercaptoethanol, 2-mercaptopropanol, 1-mercapto-2-propanol and 2-mercaptobutanol.

Nitrogen-containing compounds

Inhibitors based on nitrogen-containing compounds are the most widespread among all organic compounds containing heteroatoms [17, 28].

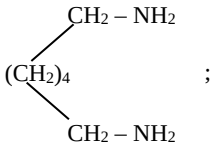
Structures of the main nitrogen-containing compounds used as active bases of carbon dioxide corrosion inhibitors:

• imidazolines

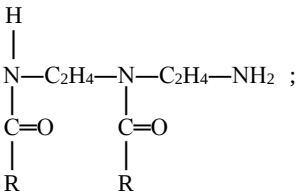


• primary amines R–NH_2;

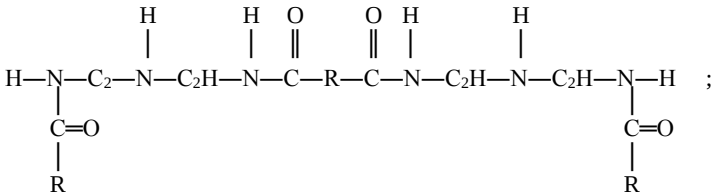
• diamines



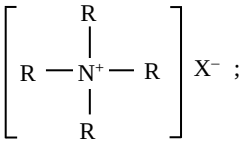
• amidoamines



• dimerized amidoamines

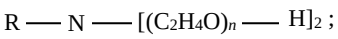


• quaternary ammonium bases (QAS)

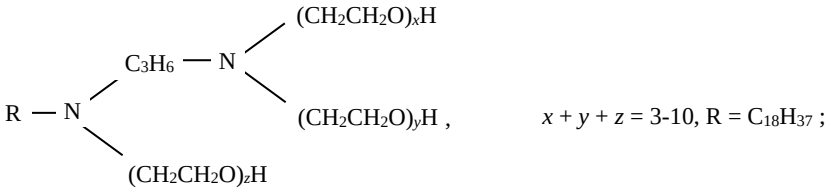


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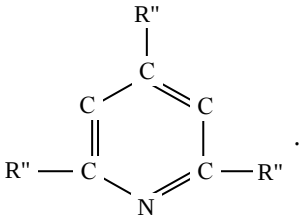
• oxyethylated primary amines



• polyethoxyalkyldiamines



• alkylpyridines



Amines, amides, imidazolines and their derivatives are used as the active base of corrosion inhibitors. Analysis of corrosion inhibitors used on the territory of the Russian Federation and produced by domestic companies shows that complex mixtures of nitrogen-containing compounds are predominantly used as the active base. Effectiveness of active bases of carbon dioxide corrosion inhibitors of domestic manufacturers: mixture of nitrogen-containing surfactants – 90 %; reaction product of tall oil with tetraethylenepentamine – 90 %; mixture of alkylimidazolines – 91 %; amido-imidosoline of fatty acids – 90 %; condensation product of fatty acids of tall oil with aminoethyl-ethanoamine – 91 %; mixture of alkylimidazolines of fatty acids C_8-C_{12} – 90 %; alkyldimethylbenzylammonium chloride – 92 %.

Amines and QAS

Primary, secondary, tertiary amines and tertiary derivatives containing a positively charged nitrogen atom covalently bonded to four organic radicals and ionically bonded to an anion are used as corrosion inhibitors. The radicals commonly used are fatty acid residues, alkyl (C_8-C_{30}), phenyl, oxy- and polyoxyalkyl.

QAS are cationic type surfactants. This means that in aqueous solutions, QAS dissociate into a positively charged radical and an acid anion. QAS have been used for a long time and widely in the oil and gas industry. They are used as individual active bases or in mixtures with other classes of compounds. Dimethyldodecylbenzylammonium chloride is an example of QAS-based CI. N-alkyl quaternary ammonium compounds with different anions have the structure of amphiphilic cationic surfactants and are therefore potential metal corrosion inhibitors.

In the research [29] a series of pyrrolidine-based quaternary ammonium salts containing hydrophobic C_{12}-C_{16} alkyl moieties and hydrophilic oxygen-containing substitutes (propargyl, dodecyl and their combination) were synthesized. High inhibitory properties of the studied ammonium compounds are primarily due to the presence of several adsorption centers. Hydrophilic fragments are chemisorbed on the metal surface to form a protective film (coating), and hydrophobic substitutes displace the adsorbed water layer to form a protective layer on the metal surface. As the alkyl chain length increases, the inhibition efficiency increases. Aliphatic hydrocarbon radicals contained in ammonium cations as well as in organic acid anions provide adsorption interaction with the metal surface.

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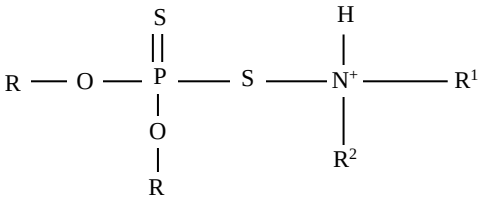


Fig.2. Structure of the O,O-diethers of dithiophosphoric acids
R is iso-$C_9H_{19}C_6H_4$, iso-$C_9H_{19}C_6H_4(OCH_2CH_2)_6$, iso-$C_4H_9$, iso-$C_8H_{17}$; R^1 – H, C_2H_5, $C_{12}H_{25}$, CH_2CH_2OH; R^2– H, CH_3, C_2H_5, $C_{12}H_{25}$, CH_2CH_2OH

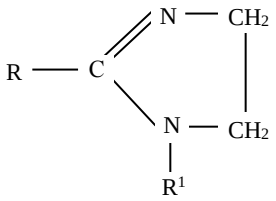


Fig.3. Structure of alkylimidazoline
R is hydrophobic, R^1 – hydrophilic

In addition, it is known that the simultaneous presence in aqueous solutions of a mixture of inhibitors exhibiting the properties of both cationic (containing ammonium cation) and anionic (containing hydrocarbon anion) surfactants can provide special properties that can significantly increase the effectiveness of anticorrosion action.

The length of alkyl substitute of dimethylbenzylammonium affects the effectiveness of corrosion inhibitor based on it [30]. The molecular structure of the model compounds includes the same polar group, dimethylbenzylammonium, and four different hydrophobic moieties with different lengths of alkyl tails (butyl (–C_4H_9), oktyl (–C_8H_{17}), dodecyl (–$C_{12}H_{25}$) and hexadecyl (–$C_{16}H_{33}$). It was found that the longer the length of the alkyl moiety, which has good adhesion to the metal surface, the higher the corrosion reduction efficiency for the homologous series evaluated. The main role of the leading group of model quaternary ammonium compounds is to form bonds of the inhibitor molecule with the metal surface, while the hydrophobicity of the alkyl tail plays a determining role in the inhibition process by displacing water molecules from the surface.

Ammonium salts of O, O-dialkyl dithiophosphoric acids (Fig.2) are effective inhibitors of carbonic acid corrosion, in the presence of which a protective effect of up to 99 % is achieved [31]. In the case of carbon dioxide corrosion, the inhibitory activity is independent of the nature of the amine and the length of the alkyl substitute in the ester group. An important feature is that the inhibitory effect of these compounds increases with increasing temperature.

Imidazolines

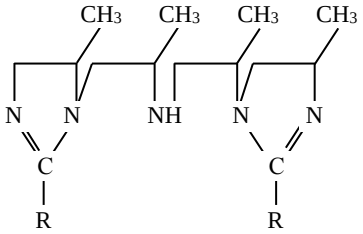
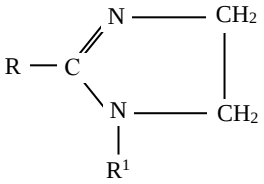
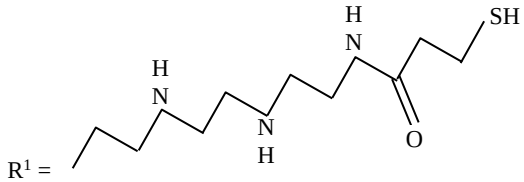
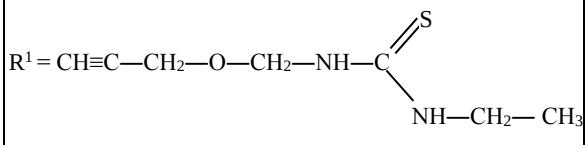
Imidazolines and their derivatives (Fig.3) are widely used as organic corrosion inhibitors in the oil and gas industry worldwide to effectively suppress CO_2 corrosion.

Imidazoline can be readily synthesized from natural fatty acids and ethylenediamines, as well as from aldehydes and diamines [20]. The use of natural fatty acids make imidazolines environmentally friendly. Imidazolines can also be derived from plant material. Thus, in [32] a hydroxyethyl imidazoline derivative was synthesized based on coffee oil and found to be highly effective in reducing carbon dioxide corrosion rate, 99.9 % at a concentration of 10 ppm. In the research [33] a novel N-(3-(2-fatty-4,5-dihydro-1H-imidazol-1-yl)propyl) – fatty amide-type surfactant was derived from fatty acids (C_{16}-C_{18}), contained in mango seeds and showed high performance under corrosive conditions of CO_2. It was previously determined that adsorption of olein-substituted imidazoline on steel surfaces creates a fully hydrophobic surface, forming a watertight barrier between the corrosive aqueous phase and the steel surface, which provides effective corrosion protection. To improve the efficiency of corrosion inhibitors, the authors [34] synthesized a number of imidazoline derivatives from oleic acid and various amines (ethylenediamine, diethylenetriamine, triethylenetetramine, tetraethylenepentamine, hydroxyethyl ethylenediamine, and polyethylenepolyamine) and showed that the efficiency of CI based on them is 97-98 %. The inhibition efficiency of imidazolines obtained by condensation of soybean oil fatty acid and various amines (DETA, TETA, TEPA) was 50-90 % [35]. Imidazoline derivatives derived from semi-purified rice bran oil exhibited high inhibitory properties up to 99.69 % for carbon steel [36].

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Table 2

Structures of the main imidazoline compounds used as active bases of inhibitors of carbonic acid corrosion

Compound	Structure	Substitutes	Reference
Bis-imidazoline		$R = C_{17}H_{33}$	[37]
Alkylimidazoline		$R = C_{17}H_{33}$ R^1=H $C_2H_4NH_2$ $C_3H_6NH_2$ $C_2H_4NHC_2H_4NH_2$ $(C_2H_4NH)_2C_2H_4NH_2$ $(C_2H_4NH)xC_2H_4NH_2$ ($x \geq 3$) C_2H_4OH	[34], [38]
		$R = C_2H_5$, $C_{18}H_{37}$ $R^1 = C_2H_4OH$	[38]
		$R = C_{17}H_{33}$ 	[39]
		$R = C_{17}H_{33}$ 	[40]

The presence of several nitrogen atoms in the structure of compounds increases their anti-corrosion ability. The authors of [37] developed a method of obtaining a corrosion inhibitor based on ethylene oxide and bis-imidazoline obtained by interaction of tetrapropylene pentamine and oleic acid, which demonstrated high efficiency of corrosion reduction in carbonate medium – 97-98 % at a concentration of 30-50 mg/g.

A number of researches are aimed at studying the adsorption and anticorrosion properties of alkylimidazolines depending on the nature of substitutes R and R^1 (Table 2). Substitutes exhibit different properties and perform different functions. The hydrophilic part provides orientation and bonding of the corrosion inhibitor to the metal surface, while the hydrophobic part provides formation of a protective adsorption barrier between the metal surface and the corrosive medium. It is still debated which substitute has a greater influence on the effectiveness of corrosion inhibitors. For example, a number of alkylimidazolines have been synthesized in the research [38] by varying the nature of both hydrophilic and hydrophobic substitutes, the most representative examples are shown in Table 2.

It was established that at the same R ($C_{17}H_{33}$) replacing the hydrogen with aminoethylene ($C_2H_4NH_2$) in the position R^1 significantly increases the CI efficiency, from 77 to 92 %. Increasing the chain length of the amine substitute does not affect the efficiency as much, and in some cases

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($C_3H_6NH_2$) decreases it. The introduction of a hydroxyethyl group into the imidazoline ring weakens the inhibitory ability of imidazoline due to an increase in its hydrophilicity, which leads to an increase in water solubility with a decrease in the insulating ability of the inhibitor film. Whereas, for the same R^1 (C_2H_4OH) replacing the alkyl chain C_{17} with C_2 decreases the CI efficiency sharply from 90 to 13 %, confirming the important role of the hydrophobic part length. The chain branching slightly changes the effectiveness of the inhibitor.

The authors [34] synthesized a series of imidazolines using oleic acid and various nitrogen- and oxygen-containing groups as substitutes (Table 2) and showed that the introduction of hydroxyethyl group increases the hydrophilicity of imidazoline, while aminoethylene increases the hydrophobicity. The effectiveness of a corrosion inhibitor is directly related to the combination of its hydrophobic and hydrophilic properties. Another important factor affecting the properties of corrosion inhibitors is the operating conditions, particularly the flow rate. Thus, at low speeds (0.3-0.6 m/s), alkylimidazolines with side substitutes $–C_2H_4NH_2$ and $–C_2H_4NHC_2H_4NH_2$ showed the highest performance, whereas at higher speeds (5.5 m/s), alkylimidazoline without side substitute R^1 had the highest efficiency.

In the research [41] a synergistic effect was found – when oleic imidazoline and mercaptoethanol were used in a 3:1 ratio, the efficiency reached 96.56 %.

In early researches it was shown that olein-substituted imidazoline is an effective base for corrosion inhibitors, and in order to improve the anticorrosion properties, the authors [39] introduced a sulfhydryl substitute into olein-substituted imidazoline (Table 2), which led to an increase in inhibition efficiency up to 95.58 %. This difference is due to the presence of an additional active adsorption center.

An inhibitor of carbon dioxide corrosion based on imidazoline derived from polyamine (triethanoltetramine, polyethylene polyamine) with carboxylic acid (oleic acid, stearic acid, acetic acid) was proposed in the research [42]. An important feature of this inhibitor is the addition of copper-containing carbon nanostructures to the obtained imidazoline, which makes it possible to reduce the working concentration of the corrosion inhibitor from 40 to 15 mg/l without loss of efficiency.

In studying the effectiveness of imidazoline-containing inhibitor of uniform and localized corrosion in the medium CO_2 [43] two main factors affecting the inhibition efficiency, i.e., inhibitor adsorption/film formation and the presence of corrosion products, were identified. The presence of corrosion products had a significant effect on both the adsorption of the inhibitor and the depth of the corrosion pit. This effect was most pronounced in the formation of a layer consisting predominantly of $FeCO_3$, while the corrosion inhibitor provided only ~25 % of the total protection.

Imidazolinthioureidooleic acid is widely used in the oil and gas industry as the basis of an effective carbon dioxide corrosion inhibitor for carbon steel, but due to the increasing depth of oil fields, improvement of its anticorrosion characteristics is required. One way of improvement is the modification of imidazolinathioureidooleic acid. For example, in [40] a modified imidazolinthioureidooleic acid (Table 2) was obtained by reaction with formaldehyde and propargyl alcohol c, which showed improved anticorrosion properties.

It was found that due to the additional adsorption center and higher hydrophobicity, the modified imidazoline forms a more stable and effective adsorption film, increasing the efficiency of the corrosion inhibitor based on it. In the research [44] branched tetraimidazoline derivatives that contain four adsorption centers were synthesized (Fig.4).

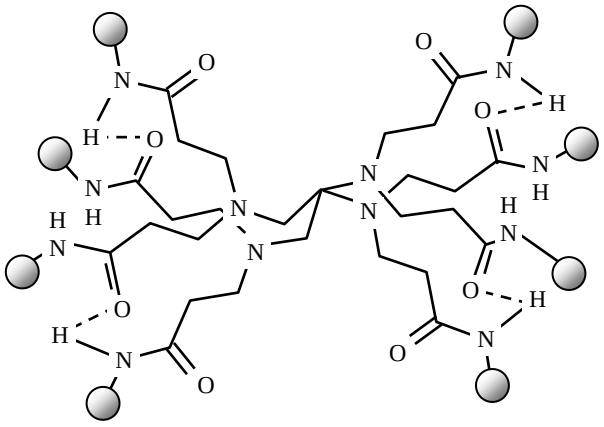


Fig.4. Structure of a branched derivative tetraimidazoline

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Fig.5. Structure of 3- and 4-pyridinecarboxaldehyde-4-phenylthiosemicarbazides

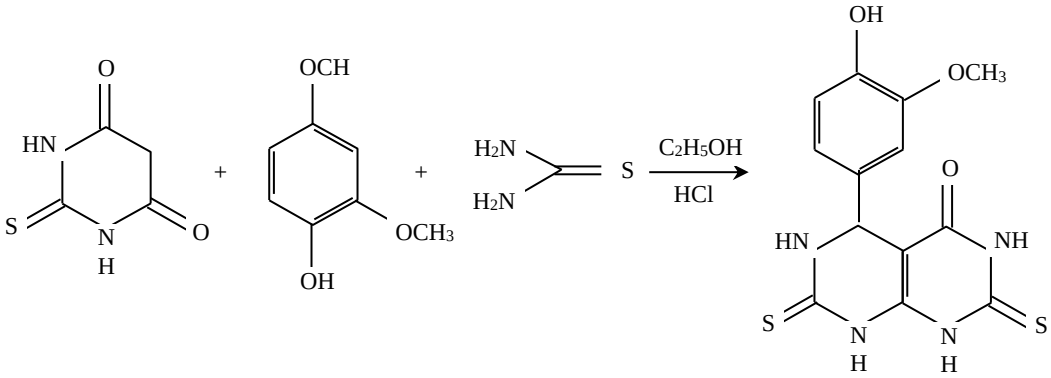


Fig.6. Synthesis scheme
5-(4-hydroxy-3-methoxyphenyl)-2,7-dithioxo-2,3,5,6,7,8-hexahydropyrimido[4,5-*d*]pyrimidin-4(1H)-one

It was found that the efficiency of the corrosion inhibitor based on the synthesized compound increases with increasing concentration and temperature and reaches 98.29 %. Scanning electron microscopy data confirm the formation of dense dendrimer-like protective films that ensure the absence of contact between the aggressive medium and the metal surface.

The pyridine Schiff base derivatives, namely 3-pyridinecarboxaldehyde-4-phenylthiosemicarbazide (3-PCPHC) and 4-pyridinecarboxaldehyde-4-phenylthiosemicarbazide (4-PCPHC) (Fig.5), showed efficacy as carbonic acid corrosion inhibitors [45]. At the same concentration, the inhibition efficiency of 3-PCPHC is higher than that of 4-PCPHC, increasing sharply with increasing concentration and remaining constant at different temperatures. According to the results of molecular dynamic simulations, both protonated and non-protonated 3-PCPHC and 4-PCPHC adsorb on Fe (110) almost parallel to the surface, forming an adsorption layer.

Pyrimidine-based compounds can exhibit high corrosion resistance activity. Thus, in [46] 5-(4-hydroxy-3-methoxyphenyl)-2,7-dithioxo-2,3,5,6,7,8-hexahydropyrimido[4,5-*d*]pyrimidin-4(1H)-one was synthesized (Fig.6) and used as a carbon dioxide corrosion inhibitor.

It was found that the high efficiency (up to 90 % at a concentration of 20 ppm) was mainly due to two factors, namely, the large number of adsorption centers (N, S and O, as well as π-electrons in the aromatic ring) and the selectivity of adsorption on the Fe (110) surface, which significantly reduced the local corrosion rate on the steel surface during sweet corrosion. This is consistent with earlier studies showing that the initiation of localized corrosion occurs in the sequence of iron crystal faces (110) > (100) > (111) given that the propagation of uniform corrosion occurs in the following order of iron crystal faces: (100) > (110) > (111) [47].

Polymer-containing compounds

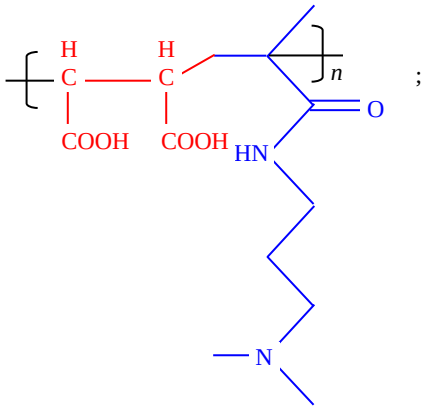
Polymeric corrosion inhibitors have a number of advantages over inhibitors with small organic molecules – easy formation of multilayer adsorption films on the metal surface and a greater number of molecule sites involved in adsorption and higher temperature resistance. According to

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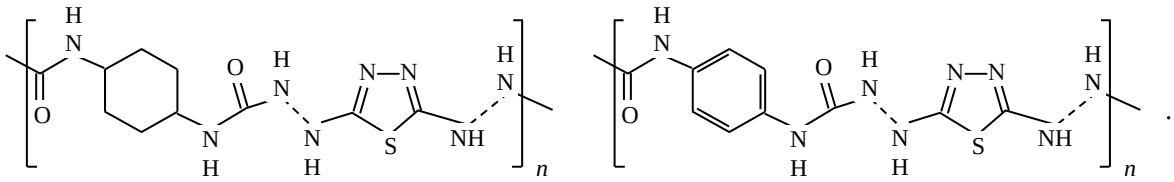
a review [48], most polymer-containing corrosion inhibitors are polyamines modified with carboxylate and heterocyclic moieties, thiols, disulfides and phosphorus-containing functional groups.

Structure of polymers used as corrosion inhibitors:

• poly(maleic acid-co-N-[3-(dimethylamino)propyl]-methacrylamide [49].



• poly(urethane-semicarbazides) containing thiadiazoles,



In the research [50] poly(maleic acid-co-N-[3-(dimethylamino)propyl]-methacrylamide) synthesized by polymerization in aqueous solution was used as the base of the corrosion inhibitor. The results showed that the polymeric corrosion inhibitor exhibited high corrosion inhibition efficiency (90.1 % at a dosage of 200 mg/l) and acted as an anodic type inhibitor by forming an adsorptive polymeric film on the metal surface.

Polysemicarbazides have good thermal and mechanical properties due to hydrogen bonding. Poly(urethane-semicarbides) containing a chain of 1,3,4-thiadiazoles were synthesized. It was found that corrosion inhibitors based on them show high efficiency, forming a strong adsorbed film. The polymer containing aromatic rings showed more activity, which is probably due to its higher stiffness and stability [51].

In [49] polyacrylamide, poly(2-methoxyaniline) and copolymer of polyacrylamide and poly(2-methoxyaniline) were synthesized and investigated as corrosion inhibitors polyacrylamide, poly(2-methoxyaniline) and copolymer of polyacrylamide and poly(2-methoxyaniline) were synthesized and investigated as corrosion inhibitors. Among all the polymers studied, poly(2-methoxyaniline) showed the highest anticorrosion efficiency, which was 80 % versus 63-74 %. The higher adsorption capacity may be due to the presence of more donor groups, which improves the coordination of the polymer to the metal surface.

The authors [52] compared the effectiveness of polypropylene glycol and polymethacrylic acid based corrosion inhibitors in the concentration range of 50-1000 ppm. The polymers were found to be mixed type inhibitors and the effectiveness of polypropylene glycol was higher, with corrosion activity increasing with increasing inhibitor concentration and decreasing with increasing temperature.

In recent years, inorganic porous materials and polymers have been widely studied for encapsulation of active substances, i.e., under certain environmental conditions, the capsules are destroyed with the release of a corrosion inhibitor [53]. For example, in work [54] the polymeric material was combined with classical organic corrosion inhibitors (Fig.7).

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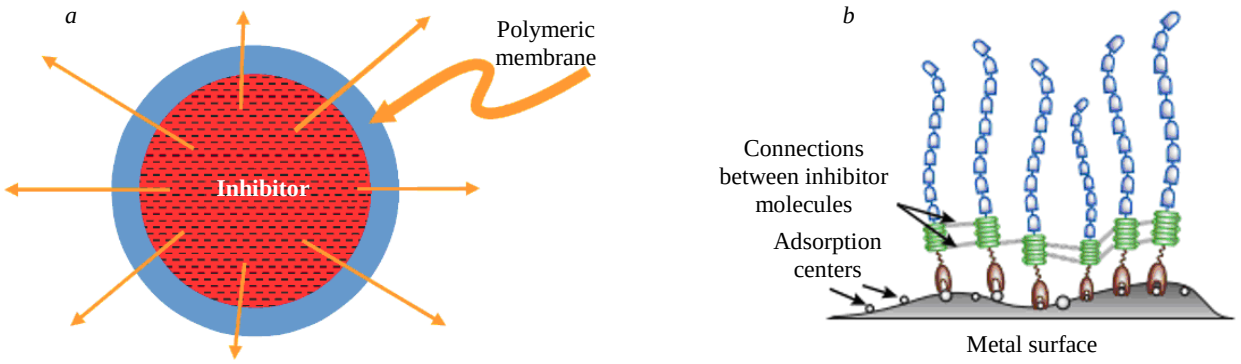


Fig.7. Structure of capsule polymer-containing corrosion inhibitor (diffusion of the active component of the inhibitor through the polymer membrane) (*a*), polymer-crosslinked surfactants (*b*)

The polymer can be used as a shell for a capsule covering the corrosion inhibitor concentrate (Fig.7, *a*). When exposed to the medium, slow uniform diffusion of the corrosion inhibitor through the organic polymer membrane of the capsule occurs. Additional components such as weighting agent and capsule wall modifier can be used to provide the required density, resistance to external influences and reagent diffusion rate through the membrane. Polymer cross-linked surfactants are polymer corrosion inhibitor molecules that have specific sites (spacers) that form an additional stable bond between them, reinforcing the film (Fig.7, *b*).

These approaches allow, on the one hand, to reduce the concentration of corrosion inhibitor without loss of efficiency, and on the other hand, to achieve a high aftereffect due to the creation of a stable film.

“Green” corrosion inhibitors

Another class of compounds actively used as environmentally safe corrosion inhibitors are substances of plant origin, which are promising due to biodegradability, availability and non-toxicity. The use of plant extracts can achieve inhibition efficiencies in excess of 80 %, making them attractive targets for research. The use of plant extracts as a crude corrosion inhibitor has been widely reported in the literature [55-57] as an alternative to classical corrosion inhibitors. The anticorrosive activity of many of the studied extracts may be related to the presence of heterocyclic components such as alkaloids, flavonoids, etc., which contribute to the formation of adsorption layer. A review of the literature on “green” corrosion inhibitors shows that the main criterion for inhibitor selection is the presence of heteroatoms (N, O, P, and S) in the composition, since hydroxyl, carboxyl and amino groups are mainly responsible for chelation and adsorption efficiency.

For example, alcoholic extracts of plants *Lycium shawii, Teucrium oliverianum, Ochradenus baccatus, Anvillea garcinii, Cassia italica, Artemisia sieberi, Carthamus tinctorius and Tripleurospermum auriculatum* were used as corrosion inhibitors. It is confirmed that these plant extracts exhibit high efficacy, which is 62-91 %. The extract of water hyacinth, a type of water weed that is often a problem for hydroelectric power plants, was also used, its effectiveness increases with increasing concentration, the optimum value being 50 ppm.

Biopolymers, especially water-soluble ones, are effective corrosion inhibitors in various aqueous environments [58]. Due to their massive functional groups, biopolymers are able to form complexes with a large area of the metal surface, providing a high degree of protection. The effectiveness of biopolymers used as corrosion inhibitors varies depending on their molecular weight, aromaticity, and the presence of groups forming bonds and adsorption centers.

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Biopolymers such as lignin [59], inulin [60], cellulose [61], starch, pectin, chitosan [62], and their mixtures are considered as promising materials for "green" corrosion inhibitors for various environments.

Natural polymers can act as additives to traditionally used nitrogen-containing corrosion inhibitors, resulting in improved efficacy through synergistic effects [63].

Natural polysaccharides can be modified with different groups to obtain highly effective corrosion inhibitors. For example, two carboxymethyl chitosan derivatives were synthesized and used in [64], which exhibited maximum efficiency (87.97 and 93.95 %) at a concentration of 100 mg/l.

When considering plant extracts and biopolymers as corrosion inhibitors, it is necessary to take into account points related to the preparation of raw materials (drying, dehydration), to the conditions and reagents for extraction, as well as to the utilization of solvents, which are often highly acidic and alkaline media. Factors such as solvent to solid ratio, solvent polarity, extraction time and temperature can significantly affect the chemical composition and physical properties of the samples and, consequently, the efficacy of the corrosion inhibitors. In addition, development of mathematical models including kinetic and mechanistic studies is required in predicting the corrosion inhibitory effect from plant extracts to increase their efficiency.

Conclusion

Modern adsorption-type corrosion inhibitors are usually a solution of one or more organic compounds with high inhibitory properties (active base) in a hydrocarbon or water-alcohol solvent. All commercially available corrosion inhibitors have an optimal area of application depending on the industry segment, composition of corrosive media and technological features of the protected objects.

The efficiency of corrosion inhibitor action is mainly determined by its adsorption properties, which depend on physical and chemical properties, functional groups, aromaticity, steric effect, electron density on donor atoms. Metal surface composition, microstructure and temperature also affect the adsorption and hence the effectiveness of the inhibitor.

Organic compounds containing heteroatoms (O, P, N, S) are currently the most studied as corrosion inhibitors to effectively suppress CO_2 corrosion. The most widely spread in Russia and in the world are corrosion inhibitors, where alkylimidazolines and other nitrogen-containing compounds act as an active base, which show high anticorrosion properties in the range of conditions. The effectiveness of commercial inhibitors from different manufacturers varies between 90-92 %. It is shown that the anticorrosion properties can be significantly improved by selecting substitutes of nitrogen-containing compounds by varying their nature, chain length, structure, etc. This approach allows not only to increase the protection efficiency up to 98-99 %, but also to reduce the corrosion inhibitor concentration up to 10 ppm. In addition, one of the effective approaches to increase the anticorrosion properties of the bases used is to increase the number of adsorption centers mainly by introducing heteroatoms and aromatic structures. Corrosion inhibitors based on sulfur-containing compounds are used less frequently, but can also exhibit high corrosion protection properties, e.g. the use of rhodanine and its derivatives can achieve protection efficiencies of up to 99 % at very low concentrations (0.1-2.5 mg/l). Phosphorus-containing corrosion inhibitors show comparable anticorrosion properties at higher concentrations (up to 60 mg/g).

One of the actual directions of research in the field of corrosion inhibitors is the use of polymeric materials, which have advantages over inhibitors with small organic molecules, which include easier formation of multilayer adsorption films on the metal surface, a greater number of adsorption sites

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and higher temperature resistance. The polymer-containing components are mostly polyamines modified with carboxylate and heterocyclic moieties, thiols, disulfides and phosphorus-containing functional groups and are used as an active base, exhibiting efficacy above 90 % at dosages up to 200 mg/l. Also polymeric materials can be used in combination with classical organic compounds, where they act as a shell for more uniform diffusion of the corrosion inhibitor, which allows to increase the efficiency of the anticorrosion process.

In recent years, substances of plant origin, which are promising due to biodegradability, availability and nontoxicity, have been actively investigated for use as environmentally safe corrosion inhibitors. The possibility of using biopolymers and polysaccharides, such as lignin, cellulose, starch, pectin, chitosan, etc., as well as their mixtures, the use of which allows achieving effective protection above 93 %, is considered. This class of compounds is used as an additive to traditionally used nitrogen-containing corrosion inhibitors, which increases the effectiveness due to synergistic effect, and as a main component, due to massive functional groups, which, adsorbed on the larger surface of the metal, provide a high degree of protection. Plant extracts also exhibit high anti-corrosion activity (above 91 %), which is attributed to the presence of heterocyclic components such as alkaloids, flavonoids, etc., which contribute to the formation of a strong adsorption layer.

Two main approaches have been proposed to improve corrosion protection in the petroleum industry. The first one is based on modification of currently used corrosion inhibitors based on nitrogen-containing compounds, which has advantages as this class is well studied in a wide range of conditions and has been successfully applied in the fields for many years. At the same time, "classical" corrosion inhibitors can be supplemented with new polymeric, biological, and nanoscale additives. Another approach is aimed at using alternative corrosion inhibitors, including those based on plant extracts and polymers, which requires more directed research and testing in real conditions, but is attractive from the point of view of the environmental performance of the applied objects.

REFERENCES

1. Ormellese M. Corrosion in Oil and Chemical Industry. Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry. Elsevier, 2018. Vol. 6.1: Corrosion and Passivation, p. 145-154. DOI: 10.1016/B978-0-12-409547-2.13434-1

2. Koryakin A.Yu., Kobychev V.F., Kolinchenko I.V., Yusupov A.D. Conditions of the carbon dioxide corrosion on the production facilities of Achimovskie deposits, methods of monitoring and forecasting. *Gas Industry.* 2017. N 12, p. 84-89 (in Russian).

3. Kasyanov A.V., Belousov A.E., Popov G.G., Bolobov V.I. Determination of factors affecting on grooving corrosion. Topical Issues of Rational Use of Natural Resources. CRC Press. 2019. Vol. 1, p. 393-399. DOI: 10.1201/9781003014577-49

4. Kantyukov R.R., Zapevalov D.N., Vagapov R.K. Analysis of the application and impact of carbon dioxide media on the corrosion state of oil and gas facilities. *Journal of Mining Institute.* 2021. Vol. 250, p. 578-586. DOI: 10.31897/PMI.2021.4.11

5. Tkacheva V.E., Markin A.N., Presnyakov A.Y. et al. Localized carbon dioxide (CO_2) corrosion of the carbon and low-alloyed steels in oilfield systems. *Bulletin of the Technological University.* 2020. Vol. 23. N 12, p. 65-75 (in Russian).

6. Vagapov R.K., Fedotova A.I., Zapevalov D.N., Strelnikova K.O. Corrosion aggressiveness of various operational factors in hydrocarbon deposits containing carbon dioxide. *Vesti gazovoy nauki.* 2019. N 2 (39), p. 129-135 (in Russian).

7. Kahyarian A., Nesic S. A New Narrative for CO_2 Corrosion of Mild Steel. *Journal of the Electrochemical Society*. 2019. Vol. 166. N 11. C3048-C3063. DOI: 10.1149/2.0071911jes

8. Ting Yan, Liang-Chen Xu, Zhuo-Xiong Zeng, Wei-Guo Pan. Mechanism and anti-corrosion measures of carbon dioxide corrosion in CCUS: A review. *iScience*. 2024. Vol. 27. Iss. 1. N 108594. DOI: 10.1016/j.isci.2023.108594

9. Ilinova A.A., Romasheva N.V., Stroykov G.A. Prospects and social effects of carbon dioxide sequestration and utilization projects. *Journal of Mining Institute.* 2020. Vol. 244, p. 493-502. DOI: 10.31897/PMI.2020.4.12

10. Askari M., Aliofkhazraei M., Jafari R. et al. Downhole corrosion inhibitors for oil and gas production – a review. *Applied Surface Science Advances*. 2021. Vol. 6. N 100128. DOI: 10.1016/j.apsadv.2021.100128

11. Petrova T.A., Epishina A.D. Anti-corrosion protection of pipelines at mining and processing enterprises. *Obogashchenie rud.* 2023. N 6, p. 52-58. DOI: 10.17580/or.2023.06.09

12. Shaposhnikov N.O., Golubev I.A., Khorobrov S.V. et al. Autoclave modeling of corrosion processes occurring in a gas pipeline during transportation of an unprepared multi-phase medium containing CO_2. *Journal of Mining Institute.* 2022. Vol. 258, p. 915-923. DOI: 10.31897/PMI.2022.92

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13. Aminova D.F., Valiakhmetov R.I. Improving the efficiency of field pipeline protection using inhibitory protection. *Transport and Storage of Oil Products and Hydrocarbon Materials.* 2021. N 1, p. 58-61 (in Russian). DOI: 10.24412/0131-4270-2021-1-58-61

14. Vagapov R.K., Zapevalov D.N. Criteria for assessing the corrosion hazard and effectiveness of inhibitory protection during operation of gas production facilities in the presence of carbon dioxide. *Nauka i tekhnika v gazovoi promyshlennosti*. 2020. N 2 (82), p. 60-70 (in Russian).

15. Kulakov P.A., Rubtsov A.V., Afanasenko V.G. et al. Influence of technical condition parameters on the residual resource of capacitive equipment. *Journal of Physics: Conference Series*. 2019. Vol. 1399. Iss. 5. N 055052. DOI: 10.1088/1742-6596/1399/5/055052

16. Verma D.K., Dewangan Y., Dewangan A.K., Asatkar A. Heteroatom-Based Compounds as Sustainable Corrosion Inhibitors: An Overview. *Journal of Bio- and Tribo-Corrosion.* 2021. Vol. 7. Iss. 1. N 15. DOI: 10.1007/s40735-020-00447-7

17. Winkler D.A., Hughes A.E., Özkan C. et al. Impact of inhibition mechanisms, automation, and computational models on the discovery of organic corrosion inhibitors. *Progress in Materials Science*. 2025. Vol. 149. N 101392. DOI: 10.1016/j.pmatsci.2024.101392

18. Junying Hu, Qi Xiong, Longjun Chen et al. Corrosion inhibitor in CO_2-O_2-containing environment: Inhibition effect and mechanisms of Bis(2-ehylhexyl) phosphate for the corrosion of carbon steel. *Corrosion Science*. 2021. Vol. 179. N 109173. DOI: 10.1016/j.corsci.2020.109173

19. Wysocka J., Cieslik M., Krakowiak S., Ryl J. Carboxylic acids as efficient corrosion inhibitors of aluminium alloys in alkaline media. *Electrochimica Acta*. 2018. Vol. 289, p. 175-192. DOI: 10.1016/j.electacta.2018.08.070

20. Hamadi L., Mansouri S., Oulmi K., Kareche A. The use of amino acids as corrosion inhibitors for metals: A review. *Egyptian Journal of Petroleum*. 2018. Vol. 27. Iss. 4, p. 1157-1165. DOI: 10.1016/j.ejpe.2018.04.004

21. Reznik V.S., Khodyrev J.P., Akamsin V.D., Galiakberov R.M., Ginijatullin R.K., Semenov V.E., Galjametdinova I.V. Patent N 2351690 RF. Method of sweet iron corrosion inhibition. Publ. 10.04.2009. Bul. N 10 (in Russian).

22. Yuanqiang Zhu, Qingqing Sun, Yuan Wang et al. A Study on Inhibition Performance of Mercaptoalcohols As Corrosion Inhibitors by First Principle and Molecular Dynamics Simulation. *Russian Journal of Physical Chemistry A*. 2020. Vol. 94. N 9, p. 1877-1886. DOI: 10.1134/S0036024420090356

23. Zubritskaja N.G., Baltser A.E., Bazanov A.G., Babenko T.G., Ivanova T.V., Shukan I.V., Barskova E.N., Gromov A.V., Podobaev A.N., Reformatskaja I.I., Ashcheulova I.I. Patent N 2430997 RF. Corrosion Inhibitor. Publ. 10.10.2011. Bul. N 28 (in Russian).

24. El Ibrahimi B., Jmiai A., Bazzi L., El Issami S. Amino acids and their derivatives as corrosion inhibitors for metals and alloys. *Arabian Journal of Chemistry*. 2020. Vol. 13. Iss. 1, p. 740-771. DOI: 10.1016/j.arabjc.2017.07.013

25. Mamedova N.A., Mamedkhanova S.A., Shakhmamedova A.G. The Synthesis and Application of Salts and Complexes on the Basis of Petroleum Acid Allyl Ester as Carbon Dioxide Corrosion Inhibitors. *Petroleum Chemistry.* 2019. Vol. 59. N 2, p. 213-219. DOI: 10.1134/S0028242119020114

26. Belarbi Z., Dominguez Olivo J.M., Farelas F. et al. Decanethiol as a Corrosion Inhibitor for Carbon Steels Exposed to Aqueous CO_2. *Corrosion*. 2019. Vol. 75. Iss. 10, p. 1246-1254. DOI: 10.5006/3233

27. Young Soo Ahn, Jovancicevic V. Patent N WO 01/12878 A1. Mercaptoalcohol corrosion inhibitors. Publ. 22.02.2001.

28. Monticelli C. Corrosion Inhibitors. Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry. Elsevier, 2018. Vol. 6.1: Corrosion and Passivation, p. 164-171. DOI: 10.1016/B978-0-12-409547-2.13443-2

29. Haque J., Jafar Mazumder M.A., Quraishi M.A. et al. Pyrrolidine-based quaternary ammonium salts containing propargyl and hydrophobic C-12 and C-16 alkyl chains as corrosion inhibitors in aqueous acidic media. *Journal of Molecular Liquids*. 2020. Vol. 320. Part B. N 114473. DOI: 10.1016/j.molliq.2020.114473

30. Moradighadi N., Lewis S., Dommguez Olivo J.M. et al. Effect of Alkyl Tail Length on CMC and Mitigation Efficiency Using Model Quaternary Ammonium Corrosion Inhibitors. Corrosion, 24-28 March 2019, Nashville, TN, USA. OnePetro, 2019. N NACE-2019-13004.

31. Badeeva E.K., Batyeva E.S., Nizamov I.S. et al. Ammonium salts of *O,O'*-dialkyldithiophosphoric acids: Effective inhibitors for carbon dioxide corrosion of mild steel on the basis of red phosphorus. *Phosphorus, Sulfur, and Silicon and the Related Elements*. 2016. Vol. 191. Iss. 11-12, p. 1640-1641. DOI: 10.1080/10426507.2016.1223662

32. Porcayo-Calderon J., Martínez de la Escalera L.M., Canto J., Casales-Diaz M. Imidazoline Derivatives Based on Coffee Oil as CO_2 Corrosion Inhibitor. *International Journal of Electrochemical Science*. 2015. Vol. 10. Iss. 4, p. 3160-3176. DOI: 10.1016/S1452-3981(23)06528-8

33. Sanchez-Salazar E., Vazquez-Velez E., Uruchurtu J. et al. Use of a Gemini-Surfactant Synthesized from the Mango Seed Oil as a CO_2-Corrosion Inhibitor for X-120 Steel. *Materials*. 2021. Vol. 14. Iss. 15. N 4206. DOI: 10.3390/ma14154206

34. Jing-Mao Zhao, Feng Gu, Tong Zhao, Rui-Jing Jiang. Corrosion inhibition performance of imidazoline derivatives with different pedant chains under three flow rates in high-pressure CO_2 environment. *Research on Chemical Intermediates*. 2016. Vol. 42. Iss. 6, p. 5753-5764. DOI: 10.1007/s11164-015-2401-y

35. Muktiarti N., Ditama I., Soegijono B. Characterization of imidazoline derivates synthesized from soybean oil fatty acids as corrosion inhibitors on mild steel. *AIP Conference Proceedings*. 2020. Vol. 2242. Iss. 1. N 020023. DOI: 10.1063/5.0007980

36. Salinas-Solano G., Porcayo-Calderón J., Martínez de la Escalera L.M. et al. Development and evaluation of a green corrosion inhibitor based on rice bran oil obtained from agro-industrial waste. *Industrial Crops and Products*. 2018. Vol. 119, p. 111-124. DOI: 10.1016/j.indcrop.2018.04.009

37. Zagidullin R.N., Mustafin A.G., Khusainova K.G., Sadykov T.T. Patent N 2756210 RF. Method for obtaining corrosion inhibitor based on polypropylene polyamine and carboxylic acid for oilfield, mineralized and hydrogen sulfide-containing media. Publ. 28.09.2021. Bul. N 28 (in Russian).

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38. Usman B.J., Ali S.A. Carbon Dioxide Corrosion Inhibitors: A review. *Arabian Journal for Science and Engineering*. 2018. Vol. 43. Iss. 1, p. 1-22. DOI: 10.1007/s13369-017-2949-5

39. Ziqi Zheng, Junying Hu, Noam Eliaz et al. Mercaptopropionic acid-modified oleic imidazoline as a highly efficient corrosion inhibitor for carbon steel in CO_2-saturated formation water. *Corrosion Science*. 2022. Vol. 194. N 109930. DOI: 10.1016/j.corsci.2021.109930

40. Yuan Lu, Wei Wang, Chen Zhang, Jingmao Zhao. A Novel Imidazoline Derivative Used as an Effective Corrosion Inhibitor for Carbon Steel in a CO_2/H_2S Environment. *International Journal of Electrochemical Science*. 2019. Vol. 14. Iss. 9, p. 8579-8594. DOI: 10.20964/2019.09.06

41. Yuanqiang Zhu, Shidong Qu, Yang Shen et al. Investigation on the synergistic effects and mechanism of oleic imidazoline and mercaptoethanol corrosion inhibitors by experiment and molecular dynamic simulation. *Journal of Molecular Structure*. 2023. Vol. 1274. Part 2. N 134512. DOI: 10.1016/j.molstruc.2022.134512

42. Zakharov A.I., Demianchenko A.O., Shevnin A.A. Patent N 2769118 RF. Corrosion inhibitor. Publ. 28.03.2022. Bul. N 10 (in Russian).

43. Amir Shamsa, Richard Barker, Yong Hua et al. Impact of corrosion products on performance of imidazoline corrosion inhibitor on X65 carbon steel in CO_2 environments. *Corrosion Science*. 2021. Vol. 185. N 109423. DOI: 10.1016/j.corsci.2021.109423

44. Yi He, Yanqiu Zhou, Ranran Yang et al. Imidazoline derivative with four imidazole reaction centers as an efficient corrosion inhibitor for anti-CO_2 corrosion. *Russian Journal of Applied Chemistry*. 2015. Vol. 88. N 7, p. 1192-1200. DOI: 10.1134/S1070427215070149

45. Yue Meng, Wenbo Ning, Bin Xu et al. Inhibition of mild steel corrosion in hydrochloric acid using two novel pyridine Schiff base derivatives: a comparative study of experimental and theoretical results. *RSC Advances*. 2017. Vol. 7. Iss. 68, p. 43014-43029. DOI: 10.1039/c7ra08170g

46. Onyeachu I.B., Quraishi M.A., Obot I.B., Haque J. Newly synthesized pyrimidine compound as CO_2 corrosion inhibitor for steel in highly aggressive simulated oilfield brine. *Journal of Adhesion Science and Technology*. 2019. Vol. 33. Iss. 11, p. 1226-1247. DOI: 10.1080/01694243.2019.1585029

47. Arafin M.A., Szpunar J.A. A new understanding of intergranular stress corrosion cracking resistance of pipeline steel through grain boundary character and crystallographic texture studies. *Corrosion Science*. 2009. Vol. 51. Iss. 1, p. 119-128. DOI: 10.1016/J.CORSCI.2008.10.006

48. Tiu B.D.B., Advincula R.C. Polymeric corrosion inhibitors for the oil and gas industry: Design principles and mechanism. *Reactive and Functional Polymers*. 2015. Vol. 95, p. 25-45. DOI: 10.1016/j.reactfunctpolym.2015.08.006

49. Azzam E.M.S., Abd El-Salam H.M., Mohamed R.A. et al. Control the corrosion of mild steel using synthesized polymers based on polyacrylamide. *Egyptian Journal of Petroleum*. 2018. Vol. 27. Iss. 4, p. 897-910. DOI: 10.1016/j.ejpe.2018.01.006

50. Tianqi Chen, Zhan Chen, Mengjin Chen, Chaoyang Fu. Evaluation of anti-corrosion performance of poly(maleic acid-co-N-[3-(dimethylamino)propyl]-methacrylamide) as novel copolymer inhibitor for carbon steel in neutral medium. *Journal of Molecular Liquids*. 2021. Vol. 338. N 116638. DOI: 10.1016/j.molliq.2021.116638

51. Al-Shihry S.S., Sayed A.R., El-Lateef H.M.A. Design and assessment of a novel poly(urethane-semicarbazides) containing thiadiazoles on the backbone of the polymers as inhibitors for steel pipelines corrosion in CO_2-saturated oilfield water. *Journal of Molecular Structure*. 2020. Vol. 1201. N 127223. DOI: 10.1016/j.molstruc.2019.127223

52. Umoren S., Solomon M.M., Israel A.U. et al. Comparative Study of the Corrosion Inhibition Efficacy of Polypropylene Glycol and Poly (Methacrylic Acid) for Mild Steel in Acid Solution. *Journal of Dispersion Science and Technology*. 2015. Vol. 36, p. 1721-1735. DOI: 10.1080/01932691.2015.1004411

53. Sun A., Cui G., Liu Q. Capsule corrosion inhibitor loaded with hyperbranched chitosan: Carbon dioxide corrosion protection for downhole pipelines in oil fields. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2023. Vol. 664. N 131106. DOI: 10.1016/j.colsurfa.2023.131106

54. Dzhanelidze S.Z., Zhuravlev V.V., Zhukov A.Yu. et al. Scale control at production wells of Gazpromneft Vostok LLC: results of field tests and technical and economic assessment of the use of encapsulated inhibitor. *PROneft. Professionally about Oil*. 2021. Vol. 6. N 1, p. 95-101. DOI: 10.51890/2587-7399-2021-6-1-94-101

55. Salleh S.Z., Yusoff A.H., Zakaria S.K. et al. Plant extracts as green corrosion inhibitor for ferrous metal alloys: A review. *Journal of Cleaner Production*. 2021. Vol. 304. N 127030. DOI: 10.1016/j.jclepro.2021.127030

56. Popoola L.T. Organic green corrosion inhibitors (OGCIs): a critical review. *Corrosion Reviews*. 2019. Vol. 37. Iss. 2, p. 71-102. DOI: 10.1515/corrrev-2018-0058

57. Reza N.A., Akhmal N.H., Fadil N.A., Taib M.F.M. A Review on Plants and Biomass Wastes as Organic Green Corrosion Inhibitors for Mild Steel in Acidic Environment. *Metals*. 2021. Vol. 11. Iss. 7. N 1062. DOI: 10.3390/met11071062

58. Shahini M.H., Ramezanzadeh B., Eivaz Mohammadloo H. Recent advances in biopolymers/carbohydrate polymers as effective corrosion inhibitive macro-molecules: A review study from experimental and theoretical views. *Journal of Molecular Liquids*. 2021. Vol. 325. N 115110. DOI: 10.1016/j.molliq.2020.115110

59. de Haro J.C., Magagnin L., Turri S., Griffini G. Lignin-Based Anticorrosion Coatings for the Protection of Aluminum Surfaces. *ACS Sustainable Chemistry & Engineering*. 2019. Vol. 7. Iss. 6, p. 6213-6222. DOI: 10.1021/acssuschemeng.8b06568

60. Gowraraju N.D., Jagadeesan S., Ayyasamy K. et al. Adsorption characteristics of Iota-carrageenan and Inulin biopolymers as potential corrosion inhibitors at mild steel/sulphuric acid interface. *Journal of Molecular Liquids*. 2017. Vol. 232, p. 9-19. DOI: 10.1016/j.molliq.2017.02.054

61. Umoren S.A., AlAhmary A.A., Gasem Z.M., Solomon M.M. Evaluation of chitosan and carboxymethyl cellulose as eco-friendly corrosion inhibitors for steel. *International Journal of Biological Macromolecules*. 2018. Vol. 117, p. 1017-1028. DOI: 10.1016/j.ijbiomac.2018.06.014

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62. Umoren S.A., Eduok U.M. Application of carbohydrate polymers as corrosion inhibitors for metal substrates in different media: A review. *Carbohydrate Polymers*. 2016. Vol. 140, p. 314-341. DOI: 10.1016/j.carbpol.2015.12.038

63. Brindha T., Malarvizhi M., Mallika J. Kinetic and thermodynamic adsorption study of mild steel corrosion and inhibition of Azadirachta Indica gum in hydrochloric acid solution. *International Journal of Current Research*. 2015. Vol. 7. Iss. 9, p. 20510-20518.

64. Qing Zhao, Jixiang Guo, Guodong Cui et al. Chitosan derivatives as green corrosion inhibitors for P110 steel in a carbon dioxide environment. *Colloids and Surfaces B: Biointerfaces*. 2020. Vol. 194. N 111150. DOI: 10.1016/j.colsurfb.2020.111150

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