Increasing Corrosion Resistance of Pressure Vessels at the Hydrostatic Pressure Testing by Using Inhibitors

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Abstract. Studies of the corrosion initiation at the pressure hydraulic test of pressure vessels during their filling, maintaining and draining are presented. It has been established that the most suitable method involves the use of corrosion inhibitors, which directly decrease the corrosion rate even in small or very small quantities. It was studied the influence of some corrosion inhibitors at different concentrations on some steel materials commonly used at pressure vessels manufacturing. The study involved the inhibitors testing both in laboratory and in factory conditions. Testing in laboratory conditions involved the analysis of the following inhibitors: urea, thiourea, triethanolamine, FINEAMIN 88 and FINEAMIN 06. The results were compared with those of the Adirol inhibitor, the currently used inhibitor. It was investigated the corrosion of the following stainless steels and unalloyed steels: A 240 grade 304, A 240 grade 316, A 516 grade 70, A 516 grade 60, P260-GH, P265, P275, P295-GH, P295, and P355. By recording the potentiodynamic polarization curves, the corrosion parameters (corrosion potential, corrosion current density, polarization resistance, corrosion rate, charge transfer coefficients for anodic and cathodic processes, inhibitors acting coefficients, and inhibition efficiencies) have been evaluated. The following corrosion inhibitor solutions were selected for testing under the factory specific conditions: Instal Protect SP at concentrations of 5%, 7.5% and 10%, ELG INCOR SP at 10% concentration, FINEAMIN 06 at 10/00 concentration and a mixture of 40mL FINEAMIN 06 + 40 mL FINEAMIN 88 SCAV25 in 40 L water. The analysed steels were A 106 grade B and A 283 grade C. Tests in laboratory conditions revealed a different behaviour of the inhibitors, depending on the analysed concentration and steel grade. The inhibitors proven as appropriate following the tests in the factory conditions were ELG INCOR SP used in industrial water (tap water), whereas the mixture of FINEAMIN 06 + FINEAMIN 88 SCAV25 had efficiency only in demineralised water.

Keywords: pressure vessel corrosion, potentiodynamic polarization, steel, corrosion inhibitors, hydrostatic pressure testing

1.Introduction

Pressure vessels are usually installed in chemical and petrochemical industries. They can be column type equipment where substance transfer processes occur (absorption, desorption, chemisorption, rectification, extraction, adsorption), tanks for chemical products storage, heat exchangers containing cooling or heating fluids, and steam condensers. They are also pressure vessels that act as buffer vessels (expansion vessels) for alternative compressors, both for aspiration and discharge. Depending on the compression steps, the pressure of the gases circulated in these pressure vessels increases even up to 300bar.These vessels are exposed to different environments and operating conditions by their scope, manufacturing process, tests they are subjected to, or storage conditions until their delivery. Therefore, they have the tendency to corrode.

Corrosion is a mechanism that cannot be entirely prevented. For a specific system, it is only possible to minimize the corrosion rate at an acceptable level [1-3]. Losses due to corrosion are not only metal losses, they are equally losses of energy and human effort. Since the corrosion phenomenon is harmful

and the losses could be significant, it is necessary to minimize the corrosion or to ensure a rigorous control. Corrosion also represents a significant factor of the equipment durability and safety.

Decreasing the corrosion rate at an acceptable level involves general measures that can be taken to protect the metal surfaces from the corrosive environment action, such as: using the corrosion resistant metals and alloys, acting on the corrosive environment, coating of metallic surfaces etc. [4-6]. There are many concerns of the research community about the general methods of protection against corrosion.

The corrosion process is involved by the pressure vessels behaviour during their filling with fluids, maintaining and draining. After the equipment manufacturing or repairing, the using capacity of a pressure vessel is being proven by a universally accepted method, namely the hydrostatic pressure testing. Hydrostatic pressure testing, also known as 'Hydrostatic Testing' or a 'Leak Test', provides a method for finding leaks or verifying performance and durability in pressure vessels.This test is carried out by filling (pressurizing) the vessel with water and the water pressure is increased, held for a certain duration, and then released [7]. As the test medium is a corrosive one the corrosion phenomenon occurs in various form [8-16]. The most critical situation is recorded after the hydraulic test, when corrosion occurs in a very short time even before the protection recommended by the designer and especially when the vessels are stored until delivery to the customer. The most severe damage of the surfaces is recorded as a result of water contact both in liquid form and vapour form inside the vessels exposed to the sun. This situation has drawn the attention of our research team and it was subjected to an analyse aiming to identify materials and methods for corrosion protection, in order to increase the vessels corrosion resistance when they are subjected to the pressure test or stored. A selected method for corrosion protection was the use of inhibitors [17-24] due to its advantages, although few studies of corrosion inhibitor addition as protection of pressure vessels were published [25,26]. Given that, the pressure vessels subjected to the hydraulic test were made of low alloyed steels and stainless steels and various inhibitors were introduced in the water environment inside the vessels.

Specialized literature reveals that many studies have been carried out in recent years, focused on improving corrosion protection by environment-friendly solutions, especially on new ecological inhibitors to reduce the corrosion rate [23,24]. The investigations are based on the idea that the majority of corrosion inhibitors are toxic for the environment while the ecologic ones (green inhibitors) are biodegradable, free of heavy metals and other toxic compounds. Herbal products used as inhibitors [27] are also less expensive, renewable and easy to obtain, but their weak point is that the new solutions identified in the literature are still in a research stage and they are to be improved in order to obtain competitive products on the market. Examples of tested ecologic inhibitors are as follows: based on vegetable oils, farming products (rise bran), herbal extracts.

For the present research, last generation inhibitors were identified, the products that are adequate to the factory conditions and protect surfaces against corrosion in certain conditions related to material, corrosive medium and environment. The aim of the paper is to study solutions to improve the quality of the interior surface of the high volume vessels (pressure equipment) made from carbon steel or stainless steel, in the above-presented context. Based on the studied references, the corrosion control by the internal environment modification has been selected for this particular corrosion type, as being the most appropriate method for protection of the equipment. This method involves the adding of corrosion inhibitors in the test medium (industrial water or demineralised water) of hydraulic test. The selected inhibitors have been organic or inorganic substances which directly influence the corrosion rate even in small or very small quantities. In general, the corrosion inhibitors are used as follows: (i) inhibitors that can be applied inside large volume vessels, by uniform spraying with compressed air, using a device coupled to the end of a hose; (ii) powder inhibitors which are used by dissolving in water, for internal preservation of the equipment in order to provide protection during hydraulic test; (iii) inhibitors which are used both to treat water during hydraulic test and as layers applied by spraying or immersion in order to protect the equipment during its transport. Thus, the following tests were performed during the research:

- tests in laboratory conditions using samples of currently used metallic materials. These tests were

performed using inhibitors selected based on market availability, a comparative analysis of corrosion effect being possible;

- tests in factory conditions, during hydrostatic pressure tests of vessels under construction. These tests were performed using last generation of inhibitors and their behaviour was established as against currently used inhibitor (Adirol), under the same conditions of metallic surface and time and the same parameters of temperature and pressure.

2. Materials and methods
2.1. Materials
During the research, the corrosion protection was conducted during the vessels filling, maintaining and draining in the laboratory, as well as in the factory conditions. For testing under the laboratory conditions, the commercial steel plate samples were taken from the steels currently used for the equipment [28-32].

We investigated in laboratory the behaviour of the following steels: A240-304, A240-316, A516 grade 70 -high quality carbon steel, A516 grade 60 -carbon *steel,* P260-GH-stainless steel, P265 - weldable steel for pressure vessel(including P265-GH), P275 – pressure vessel steel, P295-GH - a normalized pressure vessel steel [29], P295, and P355 which is the highest quality *pressure vessel steel* in common use, specified by EN10028 standards [29,30]. In general, the pressure equipment is made of weldable non-alloy and alloy steels with elevated temperature properties. They have minimum chromium content of 0.8% and maximum carbon content of 0.17%. Some normalizing rolling steels are P235GH, P265GH, P295GH, and P355GH, whereas 265, 295 and 355 samples are non-alloy quality steels; all other grades are alloy steels.

Steels for testing under the factory conditions were: A106 Gr B steel according to ASTM A 106 Gr B and A 283 Gr C steel according to ASTM A 283. The A106 grade Bsteel is a mild steel pipe material usually used in industrial plants, power plants, refineries, and chemical plants. Tensile strength carbon steels a splates consist of four grade of material (A,B,C, & D) of structural quality for general application. These steel products available in the market can be used in mechanical, structural and other engineering purposes [33-36]. Steels according ASTM A283 are only used for structural purpose, while *ASME SA283/SA283M steel as plates* could also be used in boiler and pressure vessel manufacture. Its content is: 0.24% C, 0.90% Mn, 0.03% P, 0.030% S, 0.20% Cu.

The inhibitors used for test both in laboratory and in the factory were selected according to their applicability and availability on the market. It was studied the behaviour of different types of inhibitors of different concentrations in solution, as well as their influence on corrosion of steels commonly used for pressure vessels. Adirol is the currently used inhibitor in the factory for the hydraulic test, introduced with 10% content, meaning that Adirol amounts are very high and also increasing the related costs. The new inhibitors used by us in laboratory conditions were: urea, thiourea, triethanolamine (TEA), FINEAMIN 88 and FINEAMIN 06, whereas in the factory conditions the inhibitors were Instal Protect SP, ELG INCOR SP, FINEAMIN 88, FINEAMIN 06, and a mixture of FINEAMIN 06 + FINEAMIN 88 SCAV 25.

2.2. Testing in the laboratory conditions
The corrosion tests [37-40] were performed at 25°C temperature and atmospheric pressure of 1010 ± 0.5 hPa. The polarization curves studies were conducted based on plotting in potentiodynamic regime in industrial (or tap) water (control electrolyte) and in solutions containing inhibitors. The electrochemical measurements were performed using a VoltaLab 40 potentiostat using a standard electrochemical cell with three electrodes (steel sample – working electrode, a platinum foil - auxiliary electrode, and Ag/AgCl- reference electrode) and thermostatic jacket. Before each test, the samples were polished to mirror gloss, degreased with sodium carbonate solution and washed with distilled water.

The polarization curves were recorded over a range of $\pm$ 500mV from the stationary potential of each sample, at 0.5 mV/s potential sweep rate. The soft used for representations in Tafel coordinates (log i -

E) allowed the obtaining the electrochemical parameters of the process: the corrosion potential E_{corr}, corrosion currentdensity i_{corr}, polarization resistance R_p, corrosion rate v_{cor}, charge transfer coefficients α_a, α_c for anodic and cathodic reactions, inhibitor acting coefficients f, and inhibition efficiency Z.The values of inhibition efficiency, Z were calculated with the following equation:

$$z = \frac{V_{cor}^o - V_{cor}}{V_{cor}^o} \cdot 100, \% \qquad (1)$$

where: v^o_{cor} – corrosion rate without inhibitor, mm/year and v_{cor} – corrosion rate with inhibitor, mm/year.

2.3. Testing in the factory conditions

The research was carried out by following the internal specifications related to anticorrosive protection, checking the stipulated concentrations and observing the state of corroded surface after the selected period of time. The following steps were made in order to perform the hydrostatic pressure tests:

- the vessels connections were blocked;
- the study bolts were tightened according to the 'Control tightening specification' indicated by the vessel designer;
- in case of carbon steel vessels, the water used for testing was treated with corrosion inhibitors; its quality and concentration will be established according to the manufacturing technology;
- the prepared vessel was connected to the water source;
- water filling was achieved within a free connection (untightened) at the vessel upper side;
- during water filling, it was monitored the complete air removal from the compartment being tested, through a free connection (unblocked) at the upper side. Vessels free of connections at the upper side were fitted with a facility for water filling and air removal;
- after the vessel filling, these connections were blocked and the connecting pipe between vessel and pump was connected.

Water treatment with inhibitors is performed as follows:
1. Establishing the solution concentrations;
2. Establishing the period of time for observation the sheets;
3. Applying the inhibitor according to the stated sequence;
4. Verifying the vessels surfaces and the solutions concentrations, issuing observation sheets following if there are oxidized surfaces and their size and also corroded zones identification (welded zones, etc.).

The following tests were performed:

Test 1 - aimed to analyse the corrosion behaviour of some pressure vessels made of A 283 Gr C during their filling, maintaining and draining, using Install Protect SP inhibitor at concentrations of 5%, 7.5% and 10%, and compared with Adirol, the currently used inhibitor. This inhibitor (purchased from SC LABOREX Ploieşti) is an alkaline inhibitor for passivation, containing mineral salts, which adheres as a film on the metallic surface to protect against corrosion. It is an organic and anti-crust corrosion inhibitor, based on a special mixture of anti-corrosion additives (natrium nitrite < 5%, 1H-benzotriazol< 1%, sodium molybdate < 1%), which provides protection for installations containing parts made of steel, cast iron, copper, or Al-Si alloys. The usual dosage is of 1-2 L of inhibitor of each 100 L demineralised water as thermal agent for equipment heating. The dose depends on the variety of metals which the components are made from, the hardness, the working temperature.

Test 2 - aimed to analyse the corrosion behaviour of some pressure vessels made of A 283 Gr C during their filling, maintaining and draining, using ELG INCOR SP at a concentration of 10%.ELG INCOR SP is an alkaline passive inhibitor with mineral salts content. This corrosion inhibitor based on organic nitrogen compounds adheres as a film on the metals surface to protect against corrosion.ELG INCOR SP of 10% solution is a slightly opalescent liquid, soluble in water (no precipitation) and oily when touching.

Test 3 - aimed to analyse the corrosion behaviour of some pressure vessels made of A 106 Gr B during their filling, maintaining and draining, using FINEAMIN 06. This inhibitor is an alkaline, organic liquid, soluble in water, with a characteristic smell. The product is a mixture of aliphatic polyamines for protection, volatile alkalinizing amines and polymers for cleaning/dispersing, that allow the old corrosion products removal and new corrosion prevention.

It forms a protective film, due to the existence of a large number of amine groups in polyamines. Several groups of amine molecules are bonded to the metal at several points, which ensures a much more stable bond. In addition, carbohydrates are much closer to the metal surface and provide uniform and homogeneous protection.

Test 4 – aimed to analyse the corrosion behaviour of some pressure vessels made of A 106 Gr Bsteel during their filling, maintaining and draining, using FINEAMIN 06 + FINEAMIN 88 SCAV 25, in two distinct situations: using industrial water and demineralised water as test medium. These products are corrosion inhibitors for steam generating systems and closed circuits supplied with partially or fully demineralised water (up to 220bar and 600°C) FINEAMIN 88 SCAV 25 is a volatile liquid mixture of catalytic oxygen scavenger, catalyst for steam generating systems. FINEAMIN88 SCAV 25 reacts with residual oxygen dissolved in feed water. It can be mixed with other FINEAMIN products needed for water treatment in the same dosing vessel. As advantage, it does not contain hydrazine, has a fast reaction time and minimizes corrosion caused by oxygen.

3. Results and discussions
3.1 Testing in laboratory of urea, thiourea and triethanolamine (TEA) compared to Adirol

Figures 1-10 present the recorded polarization curves for different steel types in control electrolyte (water) and in solutions containing inhibitors at concentrations 5000 ppm (50/00) urea, 5000 ppm (50/00) thiourea, 2000 ppm (20/00) TEA, and 10% Adirol, respectively.
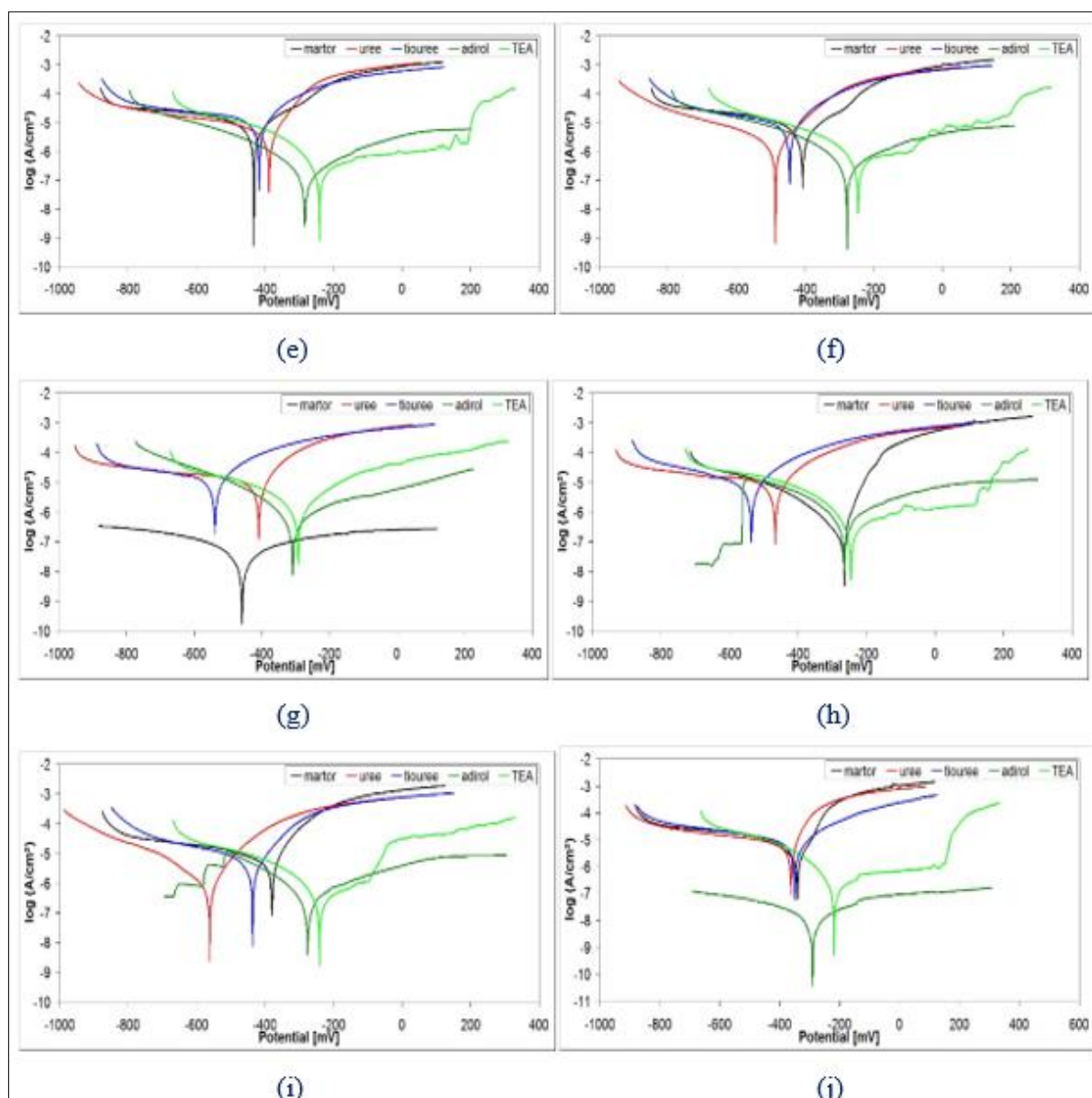

(a)

(b)

(c)

(d)
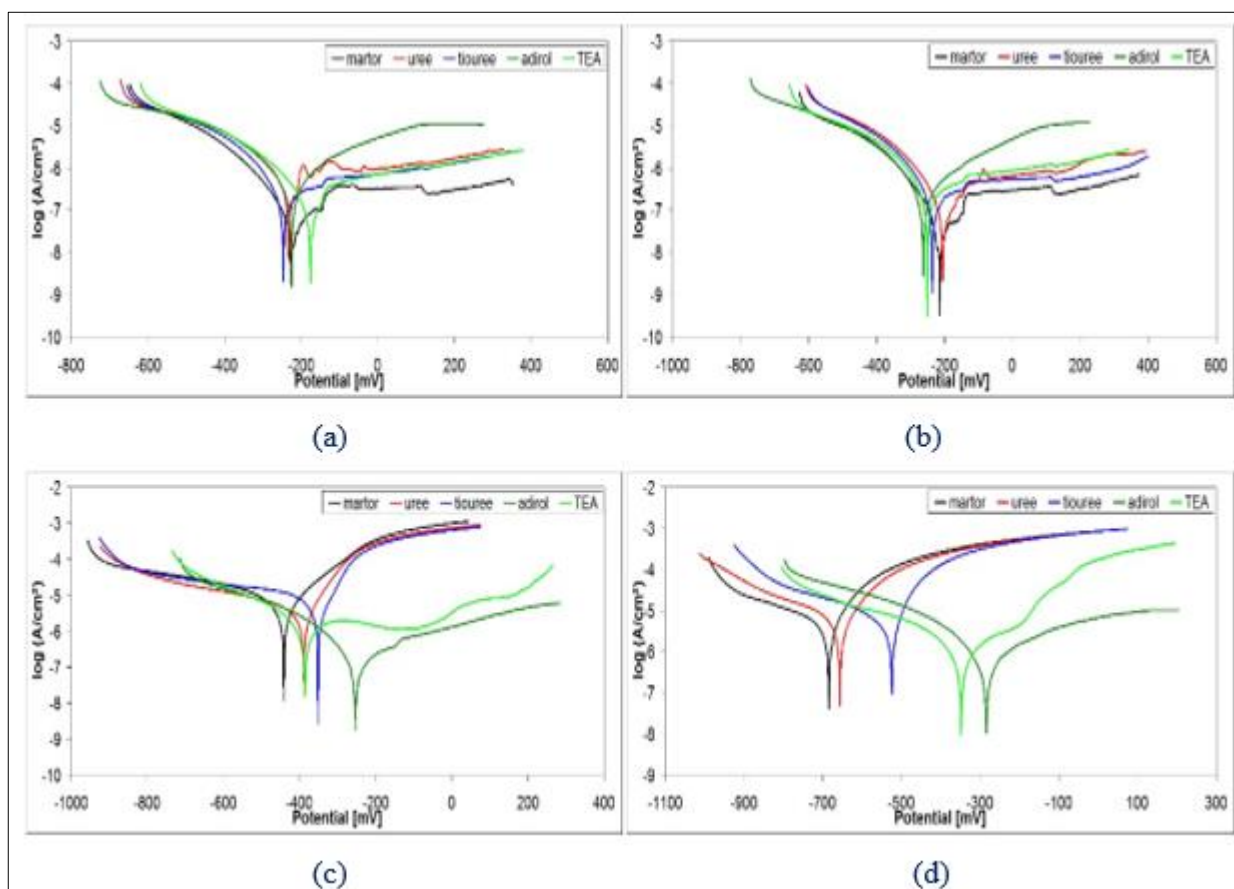
Figure 1. Potentiodynamic polarization curves recorded in various media (control electrolyte, 5000 ppm urea, 5000 ppm thiourea, 2000 ppm TEA, Adirol 10%) on different steel electrodes: a) A240-304; (b) A240-316; (c) A516-70; (d) A516grade 60; (e) P260-GH; (f) P265; (g) P275; (h) P295; (i) P295-GH; (j) P355

Table 1. Electrochemical parameters of the corrosion process using urea, thiourea, TEA and Adirol inhibitors

Steel sample	Electrolyte	E_{corr}, mV	i_{corr}, μA/cm²	R_p, kΩ.cm²	Corrosion rate, μm/year	Z, %	f	α_a	α_c
A240-304	Control	-224	0.0430	549.56	0.508	-	1	0.185	0.441
	5000 ppm urea	-232	0.3604	55.03	4.194	-738.14	8.3814	0.122	0.280
	5000 ppm thiourea	-246	0.2119	111.33	2.466	-392.79	4.9279	0.081	0.332
	10% Adirol	-224	0.2208	72.07	2.570	-413.48	5.1349	0.299	0.337
	2000 ppm TEA	-175	0.1318	185.80	1.533	-206.51	3.0651	0.271	0.301
	Control	-219	0.025	265.35	0.296	-	1	0.180	0.719

A240-316	5000 ppm urea	-204	0.141	205.36	1.651	-464	5.64	0.112	0.321
	5000 ppm thiourea	-235	0.171	131.47	1.990	-584	6.84	0.088	0.355
	10% Adirol	-262	0.204	102.35	2.374	-716	8.16	0.206	0.295
	2000 ppm TEA	-250	0.2018	104.29	2.348	-707.2	8.072	0.115	0.338
A516-70	Control	-441	3.5231	6.02	41.00	-	1	0.294	0.196
	5000 ppm urea	-389	1.7825	7.71	20.74	49.40	0.5059	0.486	0.235
	5000 ppm thiourea	-351	1.8694	4.99	21.75	46.94	0.5306	0.567	0.446
	10% Adirol	-253	0.121	180.77	1.409	96.56	0.0343	0.158	0.331
	2000 ppm TEA	-386	0.8351	24.43	9.719	76.30	0.2370	0.151	0.286
A516 grade 60	Control	-684	3.5454	5.43	41.26	-	1	0.371	0.156
	5000 ppm urea	-655	3.2655	4.74	38.00	7.89	0.9210	0.384	0.252
	5000 ppm thiourea	-524	3.7074	4.93	43.14	-4.57	1.0457	0.512	0.155
	10% Adirol	-283	0.2959	48.75	3.443	91.65	0.0835	0.304	0.376
	2000 ppm TEA	-348	0.6072	32.42	7.067	82.87	0.1713	0.223	0.271
P260-GH	Control	-433	4.6786	4.86	54.45	-	1	0.244	0.159
	5000 ppm urea	-388	2.3671	5.95	27.54	49.40	0.5059	0.507	0.208
	5000 ppm thiourea	-417	7.7168	2.99	89.80	-64.94	1.6494	0.299	0.120
	10% Adirol	-283	0.088	194.39	1.032	98.12	0.0188	0.256	0.375
	2000 ppm TEA	-241	0.2506	98.07	2.916	94.64	0.0536	0.073	0.322
P265	Control	-408	2.4087	6.03	28.03	-	1	0.343	0.301
	5000 ppm urea	-487	1.3080	15.16	15.22	45.70	0.5430	0.344	0.192
	5000 ppm thiourea	-445	4.2881	3.72	49.90	-78.02	1.7802	0.391	0.200
	10% Adirol	-278	0.2233	83.56	2.599	90.73	0.0927	0.203	0.320
	2000 ppm TEA	-245	0.4912	51.41	5.716	79.61	0.2039	0.065	0.254
P275	Control	-458	0.0178	1140	0.207	-	1	0.208	0.251
	5000 ppm urea	-408	6.7955	3.20	79.08	-38077	381.77	0.361	0.108
	5000 ppm thiourea	-538	8.2760	2.65	96.31	-46394	464.94	0.272	0.126
	10% Adirol	-308	0.3614	55.95	4.206	-1930	20.303	0.196	0.316
	2000 ppm TEA	-292	0.8353	21.67	9.721	-4593	46.927	0.295	0.278
P295-GH	Control	-380	3.4523	4.00	40.17	-	1	0.546	0.159
	5000 ppm urea	-562	0.6392	23.11	7.439	81.48	0.1851	0.477	0.251
	5000 ppm thiourea	-436	2.3065	6.05	26.84	33.19	0.6681	0.429	0.277
	10% Adirol	-275	0.1639	98.37	1.906	95.25	0.0475	0.270	0.371
	2000 ppm TEA	-241	0.3488	71.49	4.059	89.90	0.1010	0.088	0.288
P295	Control	-267	0.1231	92.24	1.432	-	1	1.090	0.348
	5000 ppm urea	-467	3.0030	4.06	34.94	-2339.4	24.395	0.468	0.319
	5000 ppm thiourea	-536	5.3486	4.00	62.24	-4244.9	43.449	0.296	0.149
	10% Adirol	-265	0.3986	51.96	4.639	-223.8	3.2380	0.204	0.256
	2000 ppm TEA	-245	0.3710	72.66	4.317	-201.4	3.0138	0.074	0.293
	Control	-340	2.1923	7.12	25.51	-	1	0.392	0.204

P355	5000 ppm urea	-362	3.7886	3.94	44.09	-72.81	1.7281	0.622	0.135
	5000 ppm thiourea	-349	4.3905	4.93	51.09	-100.26	2.0027	0.244	0.149
	10% Adirol	-290	0.002	3540	0.023	99.91	0.0009	0.684	0.719
	2000 ppm TEA	-218	0.1864	126.74	2.169	91.50	0.0850	0.093	0.338

The results of testing of solutions containing urea, thiourea and TEA in comparison to currently used Adirol inhibitor, revealed that Adirol and TEA acted as anodic inhibitors reducing the rate of corrosion reaction, increasing the anodic overvoltage simultaneously with the shift of corrosion potential to more electropositive values. This category usually includes strong oxidizing inhibitors which often produce "auto-passivation" and inhibitors that form insoluble products with ions of corroded metal. Urea also acted as an anodic inhibitor in case of A516-70, A516-grade 60, P260-GH steels while it acts as a cathodic inhibitor for P265, P295-GH samples by decreasing the rate of cathodic reaction either by increasing the overvoltage of this reaction or by reducing the concentration of the oxidizing agent following a chemical reaction therewith. At the same time, the corrosion potential in solutions with urea became more negative.

Figures 1 and 2 indicate that the four inhibitors used in this study have potentially corrosion inhibition role, which is confirmed by the values of the electrochemical parameters shown in Table 1.
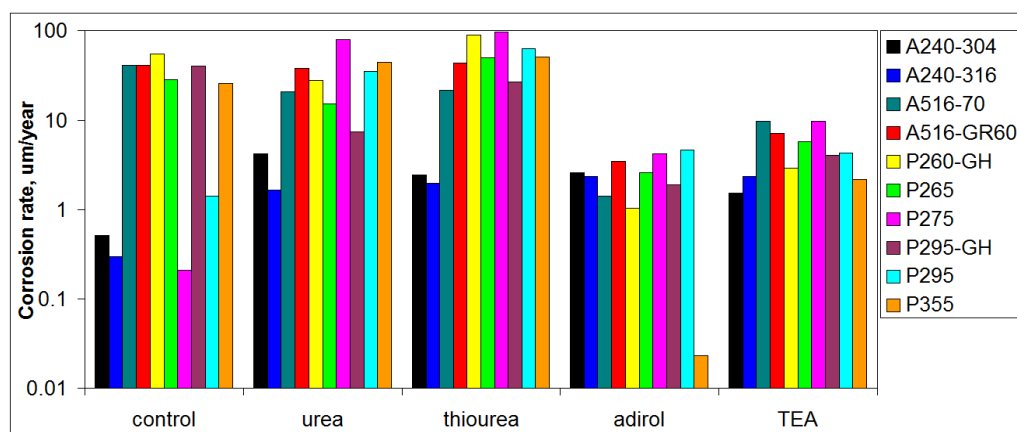

Figure 2. Corrosion rates for various steels in control electrolyte and in solutions containing urea, thiourea, TEA and Adirol as inhibitor

Figure 2 shows that lower values of the corrosion current are obtained in the presence of Adirol and TEA for the most samples, except for A240-304, A240-316, P275, P295 steels where, on the contrary, higher values of the corrosion current are recorded. This means that the inhibitors acted in some cases as corrosion accelerators and, therefore, there are not recommended. In case of using urea as inhibitor at a concentration of 5000 ppm, it can be noticed that it presents an inhibitory effect in case of A516-70, A516 grade 60, P260-GH, P265, P295-GH samples, not as strong as in case of 10% Adirol. The weakest inhibitory effect is recorded for using thiourea at a concentration of 5000 ppm and it occurs only in cases of A516-70 and P295-GH samples.

The data presented in Table 1 reveals the existence of a corrosion control both anodic (for Adirol, TEA and urea inhibitors) and cathodic (for the urea inhibitor), a fact confirmed by low values of charge transfer coefficients for anodic and cathodic reactions. Low values of these coefficients highlight the specific adsorption of the inhibitor on the metal surface. It is assumed that nitrogen and oxygen atoms are the active centres of the inhibitor related the adsorption on the metal surface. The high electronegativity of nitrogen and oxygen atoms determine Adirol and urea to act as efficient inhibitors against corrosion.

3.2 Testing in laboratory of FINEAMIN 88 and FINEAMIN 06 inhibitors

Tests for investigation the influence of FINEAMIN 88 (F88) and FINEAMIN 06 (F06) inhibitors were performed at 15°C temperature, atmospheric pressure 1010±5hPa in solutions with inhibitor concentrations of 10%, 7.5%, 5% and 0.5%. The potentiodynamic polarization curves for different steel typesin control electrolyte (water) and in solutions with different inhibitor concentrations are presented in Figure 3 (for FINEAMIN 88) and Figure 4 (for FINEAMIN 06).
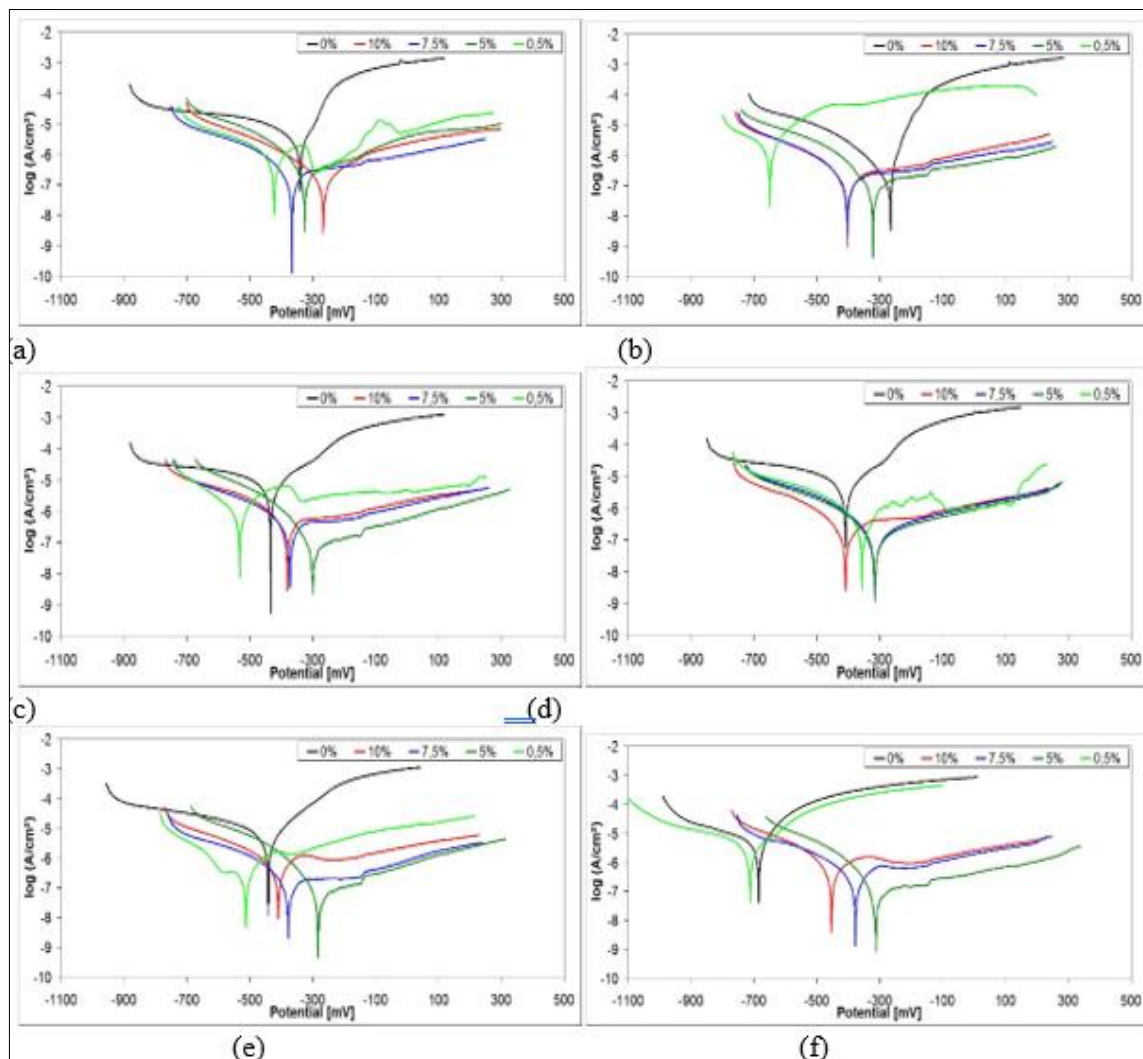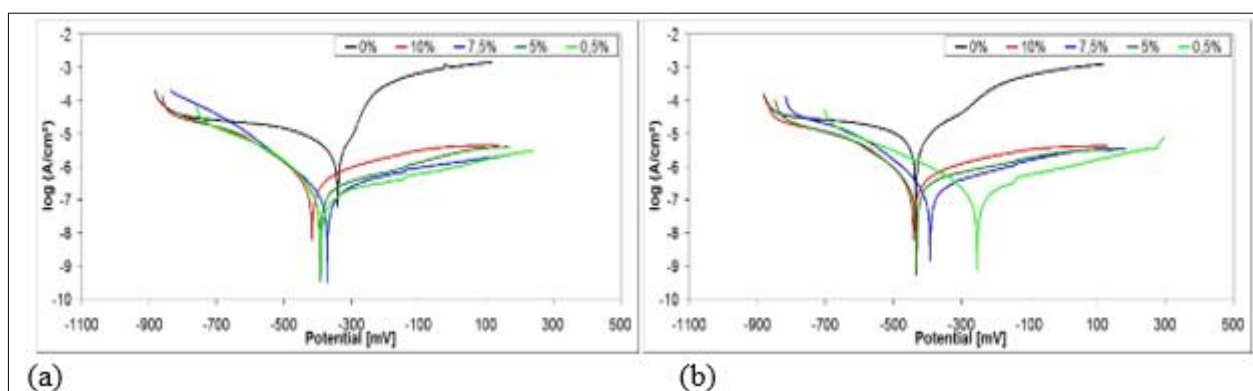

Figure 3. Potentiodynamic polarization curves recorded in control electrolyte and solutions With 0.5%, 5%, 7.5% and 10% FINEAMIN 88 inhibitor on different steel electrodes:
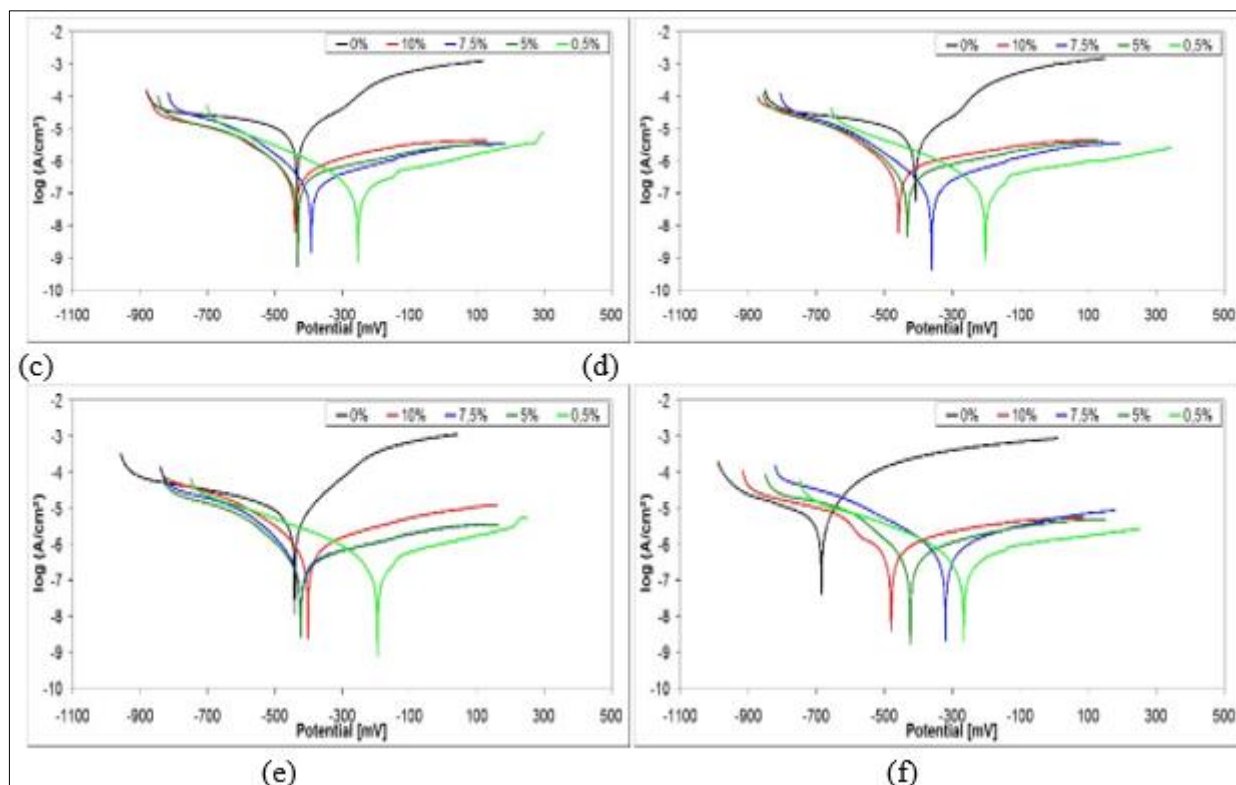(a) P355; (b) P295; (c) P275; (d) P265; (e) A516 grade 70; (f) A516 grade 60

Figure 4. Potentiodynamic polarization curves recorded in control electrolyte and solutions with
0.5%, 5%, 7.5% and 10% FINEAMIN 06 inhibitor on different steel electrodes:
(a)P355; (b) P295; (c) P275; (d) P265; (e) A516 grade 70; (f) A516 grade 60

Table 2. Electrochemical parameters of the corrosion process
using FINEAMIN 88 and FINEAMIN 06 inhibitors

Steel sample	Electrolyte	E_{corr}, mV	i_{corr}, µA/cm²	R_p, kΩ.cm²	Corrosion rate, µm/year	Z, %	f	$α_a$	$α_c$
A516-70	Control	-441	3.5231	6.02	41.00	-	-	0.294	0.196
	F88-10%	-410	0.2636	56.27	2.039	92.52	0.0748	0.327	0.323
	F88-7.5%	-377	0.0973	208.68	0.753	97.24	0.0276	0.153	0.318
	F88-5%	-283	0.0667	519.20	0.516	98.11	0.0189	0.058	0.367
	F88-0.5%	-512	0.1852	78.08	1.433	94.74	0.0526	0.419	0.209
	F06-10%	-401	0.2066	52.72	1.598	94.14	0.0586	0.397	0.501
	F06-7.5%	-422	0.2168	91.27	1.677	93.85	0.0615	0.144	0.332
	F06-5%	-422	0.1877	109.48	1.452	94.67	0.0533	0.155	0.307
	F06-0.5%	-194	0.1282	143.03	0.992	96.36	0.0364	0.247	0.266
A516-60	Control	-684	3.5454	5.43	41.26	-	-	0.371	0.156
	F88-10%	-453	0.4074	47.86	3.151	88.51	0.1149	0.200	0.301
	F88-7.5%	-377	0.2038	100.88	1.576	94.25	0.0575	0.234	0.273
	F88-5%	-313	0.1245	305.40	0.963	96.49	0.0351	0.022	0.323
	F88-0.5%	-711	1.9388	8.66	15.00	45.31	0.5468	0.268	0.253
	F06-10%	-479	0.2923	53.78	2.261	91.76	0.0824	0.257	0.329
	F06-7.5%	-319	0.3233	66.89	2.501	90.88	0.0912	0.216	0.258
	F06-5%	-423	0.3026	79.48	2.341	91.46	0.0853	0.153	0.262
	F06-0.5%	-266	0.0837	131.04	0.648	97.639	0.0236	0.393	0.460
P265	Control	-408	2.4087	6.03	28.03	-	-	0.343	0.301
	F88-10%	-408	0.1124	158.36	0.870	95.33	0.0466	0.203	0.319
	F88-7.5%	-314	0.0880	222.54	0.681	96.35	0.0365	0.185	0.324
	F88-5%	-315	0.0955	254.56	0.740	96.04	0.0396	0.130	0.277
	F88-0.5%	-356	0.3033	84.81	2.346	87.41	0.1259	0.255	0.246
	F06-10%	-457	0.3653	65.44	2.826	84.83	0.1517	0.134	0.271
	F06-7.5%	-360	0.1004	213.06	0.777	95.83	0.0417	0.195	0.296
	F06-5%	-431	0.2271	91.17	1.757	90.57	0.0943	0.152	0.308

|									
	F06-0.5%	-202	0.0694	259.93	0.538	97.12	0.0288	0.234	0.334
	Control	-433	4.6786	4.86	54.45	-	-	0.244	0.160
	F88-10%	-381	0.3416	75.61	2.642	92.70	0.0730	0.110	0.234
	F88-7.5%	-371	0.1867	93.70	1.445	96.01	0.0399	0.209	0.321
P275	F88-5%	-300	0.0734	478.03	0.569	98.43	0.0157	0.084	0.390
	F88-0.5%	-532	0.7382	22.51	5.711	84.22	0.1578	0.318	0.233
	F06-10%	-439	0.2191	86.09	1.695	95.32	0.0468	0.204	0.311
	F06-7.5%	-391	0.1259	156.97	0.974	97.31	0.0269	0.173	0.333
	F06-5%	-431	0.2147	113.85	1.661	95.41	0.0459	0.130	0.281
	F06-0.5%	-253	0.0883	249.26	0.684	98.11	0.0189	0.184	0.268
	Control	-267	0.1231	92.24	1.432	-	-	1.090	0.348
	F88-10%	-402	0.0943	171.02	0.730	23.40	0.7660	0.221	0.346
	F88-7.5%	-402	0.0914	191.03	0.708	25.75	0.7425	0.183	0.349
P295	F88-5%	-321	0.0503	278.31	0.389	59.14	0.4086	0.259	0.411
	F88-0.5%	-649	1.2040	11.38	9.315	-878.06	9.7807	0.420	0.273
	F06-10%	-469	0.6498	65.84	5.027	-427.86	5.2786	0.043	0.099
	F06-7.5%	-437	0.3020	54.72	2.336	-145.33	2.4533	0.232	0.372
	F06-5%	-417	0.3130	81.73	2.421	-154.26	2.5426	0.120	0.265
	F06-0.5%	-230	0.0140	950.59	0.109	88.63	0.1137	0.433	0.918
	Control	-340	2.1923	7.12	25.51	-	-	0.392	0.204
	F88-10%	-265	0.1208	164.80	0.935	94.49	0.0551	0.226	0.251
	F88-7.5%	-366	0.1019	152.89	0.789	95.35	0.0465	0.254	0.368
P355	F88-5%	-325	0.2332	94.92	1.804	89.36	0.1064	0.111	0.310
	F88-0.5%	-422	0.6558	34.00	5.074	70.09	0.2991	0.189	0.203
	F06-10%	-415	0.2360	91.43	1.826	89.23	0.1076	0.168	0.275
	F06-7.5%	-370	0.0728	234.61	0.563	96.68	0.0332	0.235	0.360
	F06-5%	-391	0.0676	188.86	0.523	96.92	0.0308	0.323	0.487
	F06-0.5%	-389	0.1119	335.14	0.866	94.90	0.0510	0.073	0.323
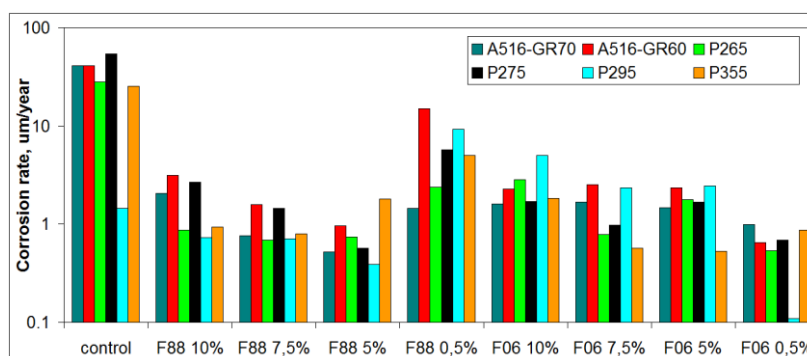
Figure 5. Corrosion rates for various steels in control electrolyte
(water) and in solutions containing FINEAMIN 88
and FINEAMIN 06 as inhibitors

The data listed in Table 2 reveal the existence of a predominantly anodic effect for the both inhibitors, for all samples at almost all concentrations, and in very small cases a cathodic effect, a fact confirmed by low values of charge transfer coefficients for anodic and cathodic reactions. The low values of these coefficients highlight the specific adsorption of the inhibitor on the metal surface. It is assumed that the active centres of the inhibitor regarding adsorption on the metal surface are nitrogen and oxygen atoms. The high electronegativity of the nitrogen and oxygen atoms determines these inhibitors to act efficiently against corrosion Analysing the electrochemical parameters determined from the Tafel polarization curves, it can be concluded that inhibitors have a inhibitory efficiency of over 90% for all concentrations in electrolyte, except for P295 sample where the efficiency is lower, and at some concentrations they act as corrosion process accelerator.

Figure 5 shows that the lowest values of the corrosion rate are obtained for F88 at 5%, respectively for F06 at 0.5% for the most samples. The weakest inhibition effect is obtained for F88 at 0.5%. In case of F06, it is noticed that the inhibition efficiency varies inversely proportional to its concentration in

electrolyte. According to the data presented in Table 2, the inhibition efficiency of F88 increases as its concentration decreases from 10 to 5%, where the maximum inhibition efficiency is reached. Then the Z value decreases as F88 concentration decreases.

In case of A516 grade 70 and A516 grade 60 steels the presence of 10% Adirol exhibits a higher inhibition efficiency than F88 at the same concentration. In case of P265 sample, the efficiency at 10% inhibitor is higher for F88 and its maximum value is for 7.5% concentration.

In case of P275 and P295 samples the Adirol addition in solution has a negative inhibition efficiency which actually transforms it into a corrosion accelerator. The P355 steel is the only sample for which the Adirol inhibition efficiency is superior to F88 inhibitor; however, the difference is small, at only 5% (94.48% for F88 in comparison to 99.90% in case of Adirol).

Concluding the above stated issues, it can be said that the F88 inhibitor showed a better inhibition efficiency for all steels, even at its lower concentrations, unlike Adirol which actually acted as a corrosion accelerator for several samples. Therefore, for scientific and economic reasons, it is recommended to use the F88 inhibitor. The results of this study present a significant importance, both in terms of equipment safety functioning and maintenance costs.

As it can be seen from the laboratory measurements, choosing an optimal inhibitor is a very difficult task because the inhibition efficiency depends on many parameters (nature of the substrate to be protected, nature of the corrosive agent, inhibitor concentration, operating temperature, pressure, relative humidity, dissolved gas concentration etc.). The weak point of this study is the absence of measurements at different temperatures and conducting gravimetric experiments as corrosion tests. An aspect that can also be improved in the future is a large extent of inhibitor concentrations to be studied.

3.3. Testing in the factory conditions

The testing in the specific conditions of the factory involved the following solutions containing corrosion inhibitors: Instal Protect SP with concentrations of 5%, 7.5% and 10%, 10% ELG INCOR SP, 10/00 FINEAMIN 06 and a mixture of 40mL FINEAMIN 06, 40 mL FINEAMIN 88 SCAV25 dissolved into 40 L water. Steels under corrosion testing were A106 grade B and A 283 grade C. Based on the obtained results, the following aspects has been revealed:

Test no. 1 showed that corrosion rate decreases linearly with Instal Protect SP concentration. Although corrosion rate values are not shown, we present here some photographic images (Figures 6 and 7). Thus, it can be seen that the proposed inhibitor does not achieve the currently used inhibitor performances.
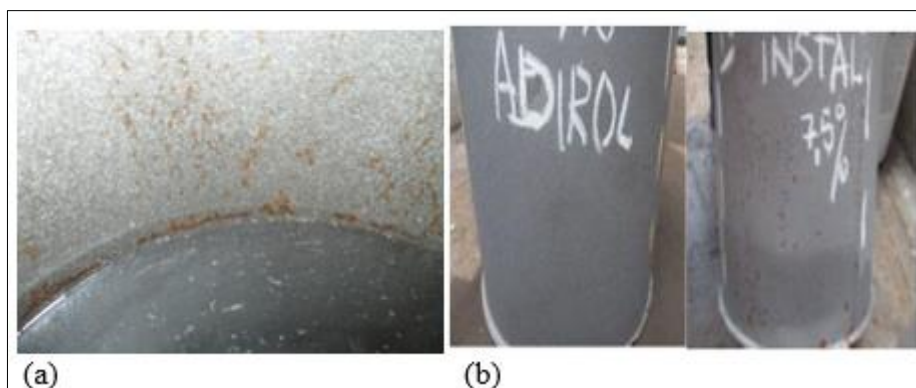

Figure 6. Aspect of the corroded area (A106 grade B stainless steel):
(a) after immersing 24 h in the 5% Instal Protect SP solution;
(b) A comparison of the examined areas after 24 h immersion in either
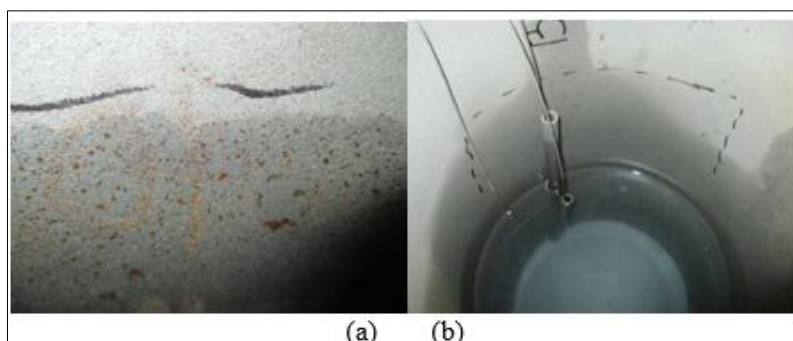10% Adirol or 7.5% Instal Protect SP solutions

Figure 7. Comparative aspects of corroded area (A106 grade B
Stainless steel) after 24 h immersion in: (a) 10% Instal Protect
SP solution; (b) 10% Adirol solution

Test no. 2 reveals that ELG INCOR SP does not precipitate at 10% concentration in solution and it has a slightly oily appearance, a behavior that favours the corrosion protection role. Also, there were not revealed corroded areas on the metallic zone in contact with ELG INCOR SP solution (Figure 8). On the contrary, the blasted area after a contact with water without inhibitor has an easy oxidized aspect and traces of rust appeared, that demonstrates and certifies the favourable influence of the corrosion inhibitor. Therefore, the test showed that the 10%ELG INCOR SP solution is conforming for metal surfaces protection and even for corrosion protection during hydrostatic pressure tests.

Figure 8. Aspect of the tested area
(A106 grade B stainless steel) after
immersing 24 h in
10% ELG 0INCOR SP solution

Test no. 3 investigated the action of solution with 10/00 FINEAMIN 06 inhibitor and showed that at this concentration the product is not conforming for corrosion protection during hydrostatic tests. Testing reveals that the corroded aspect of metallic area is similar to the untested one (Figure 9). However, it was noticed a corrosion of the tested area situated above the solution after 20 h, 24 h and 92 h of working. Also, corrosion products were noticed on the vessel wall both on the surface and on solution delimitation areas.
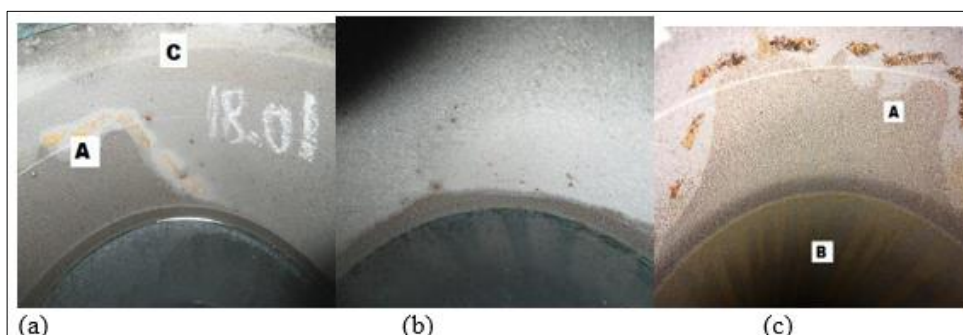

Figure 9. Testing of 10/00 FINEAMIN 06 inhibitor solution (A106 grade B
stainless steel): (a) Comparison of the aspects of A zone in contact with inhibitor and
C zone immersed in water; (b) Occurrence of corrosion products; (c) Detail of the
A- tested zone and B- zone immersed for 20 h with inhibitor solution

Test no. 4 used the mixture of FINEAMIN 06 and FINEAMIN 88 SCAV25 with prepared concentration. The results showed that this mixture is not conforming for metal surfaces protection or corrosion protection during hydrostatic tests using industrial water as solvent, as Figure 10 shows. However, the results regarding corrosion protection are better using demineralized water (Figure 11).
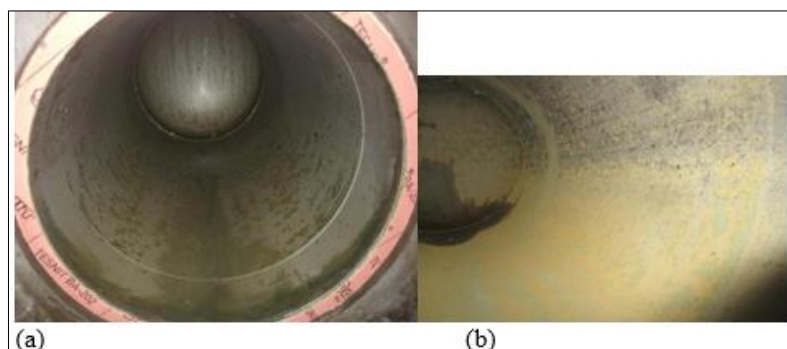

Figure 10. Images of corrosion of internal surface (A106 grade B stainless steel) after maintaining in FINEAMIN 06 and FINEAMIN 88 SCAV25 solution using industrial water and after draining (a) and after drying (b)
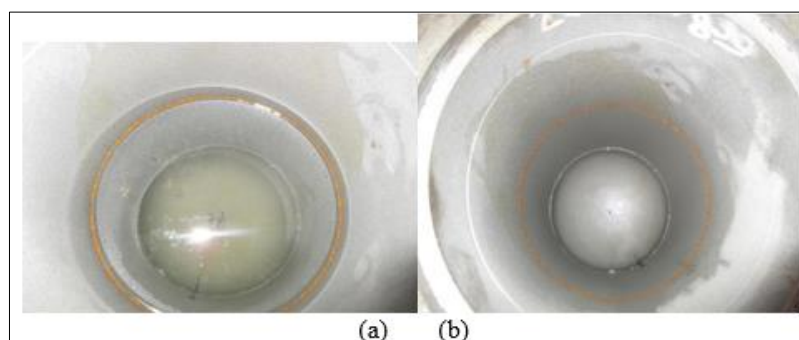
Figure 11. Internal surface aspect (A106 grade B stainless steel) after 42 h immersion in FINEAMIN 06 and FINEAMIN 88 SCAV25 diluted with demineralized water and after draining (a) and after drying (b)

It was revealed in Figure 11 that after 48 h from the introduction of the inhibitor solution into the vessel the internal surface is appropriate, except for the upper delimitation area of the solution, where traces of oxides occurred.

4. Conclusions

The study was successful in identifying some efficient and cost-effective inhibitor solutions for internal corrosion protection of high volume pressure vessels of carbon steels and stainless steels, in order to increase the corrosion resistance at hydraulic pressure test. It was established an alternative solution to the present one, regarding the chemical nature and concentration of inhibitors, which are acceptable both technically and economically. The selected inhibitors whose influence on metal corrosion was tested both in laboratory and the factory conditions were: urea, thiourea, triethanolamine (TEA), Adirol, Instal Protect SP, ELG INCOR SP, FINEAMIN 88, FINEAMIN 06, and mixture of FINEAMIN 06 + FINEAMIN 88 SCAV 25.

4.1 Testing in laboratory condition

A most important fact is that an inhibitor either can protect against corrosion or can act as a corrosion accelerator, depending of its concentration in solution. Following the analysis of the electrochemical

parameters determined from the polarization curves by the extrapolation method of the Tafel slopes, it was concluded that:

- Adirol has an inhibition efficiency over 90% at 10% concentration, except for A240-304, A240-316 and P295 steels where its behaviour seems to be a corrosion process accelerator;

- urea shows an inhibition efficiency of about 45-50% at a concentration of 5000 ppm for P265, P260GH and A516-70 samples, whereas for the P295-GH sample, the inhibition efficiency is over 80%;

- thiourea shows only a relatively low inhibition efficiency, of about 47% for A516-70 sample and 33% for P295-GH sample;

- TEA shows an inhibition efficiency in the range of 76-91% at 0.2% concentration, except for A240-304, A240-316 and P295 samples where its behaviour is of a corrosion process accelerator;

- FINEAMIN 06 and 88 have inhibition efficiency over 90% for all the concentrations, except for P295 where the efficiency is lower, whereas for some concentrations its behaviour is of a corrosion process accelerator.

4.2 Testing in factory conditions

On the basis of corrosion rate values and photographic images we noticed that:

- using Instal Protect inhibitor, although the corrosion rate proportionally decreases with increased concentration, it does not achieve the currently required inhibitor performances;

- theELG INCOR 10% inhibitor solution is CONFORMING for both metal surfaces protection and corrosion protection during hydrostatic tests.

- the FINEAMIN 06 inhibitor at selected concentration (10 mL inhibitor with 10 L water) IS NOT CONFORMING for metal surfaces protection or for corrosion protection during hydrostatic tests. To be noted that our test has been performed using industrial water as solvent, not demineralized water as prescribed by specifications.

- the mixture of FINEAMIN 06 and FINEAMIN 88 SCAV25 at prepared concentration using industrial water IS NOT CONFORMING for metal surfaces protection or for corrosion protection during hydrostatic tests. However, this mixture of FINEAMIN 06 and FINEAMIN 88 SCAV25 prepared using demineralized water IS CONFORMING for both metal surfaces protection and corrosion protection during hydrostatic test.

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