Evaluation of corrosion inhibition efficiency of Inkort 8MZ.VN applied in diesel generator cooling system operating in marine environment

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ABSTRACT

This study investigates the corrosion inhibition performance of the Inkort 8MZ.VN inhibitor on CT3 carbon steel in 3.5% NaCl solution, corresponding to the salinity of seawater in Vietnamese coastal regions. The optimal inhibition efficiency (> 99%) was achieved with 2% Inkort 8MZ.VN, as evidenced by a significant decrease in corrosion rate, reduction in anodic/cathodic current densities, and a two-order-of-magnitude increase in total corrosion resistance ($R_n = R_{film} + R_{ct}$). EIS analysis using a simulated Randles circuit confirmed the formation of a protective film (R_{film}) atop the electrical double layer, leading to reduced C_{dl} and enhanced R_{ct}. These effects are consistent with microstructural observations from SEM. The results demonstrate that Inkort 8MZ.VN at its optimal concentration effectively protects against chloride-induced corrosion in diesel generator cooling systems operating in marine environment.

Keywords: Steel CT3; Corrosion inhibitor; inkort 8MZ; Corrosion in NaCl solution; Electrochemistry.

1. INTRODUCTION

The corrosion of carbon steel in chloride-rich environments remains a critical issue, particularly in cooling water systems exposed to seawater salinity [1, 2]. Inhibitor-based protection has become a sustainable and cost-effective approach, especially as regulatory restrictions reduce the use of toxic chromates [3]. Recent studies (2020 - 2024) highlight the promise of sodium silicate and related compounds as efficient, environmentally friendly corrosion inhibitors [4-6]. These compounds provide protection primarily by forming adherent, insoluble films on steel surfaces, thereby suppressing anodic dissolution and cathodic reactions [7].

De Ketelaere et al. [4] demonstrated inhibition efficiencies up to 99.8% for carbon steel in 3 wt.% NaCl solution with sodium silicate, attributing the protection to silicate film formation. Li et al. [5] showed similar behavior in Mg alloys, with over 99% efficiency and a significant increase in charge transfer resistance (Rct). In parallel, Ahmed et al. [6] reviewed recent advances in organic and inorganic inhibitors, emphasizing the synergy between environmentally benign chemistry and robust protective films.

Electrochemical methods remain central to evaluating inhibitor performance. Potentiodynamic polarization provides direct information on anodic and cathodic kinetics [8], while electrochemical impedance spectroscopy (EIS) offers mechanistic insights through equivalent circuit modeling [9]. Advanced approaches, including Bayesian model selection, have been introduced to improve reliability in interpreting EIS data [10-12]. Despite promising results with sodium silicate, little research has been reported on Inkort 8MZ.VN, a silicate-based inhibitor developed under the Ministry of National Defense in Vietnam. This work, therefore, aims to: (i) determine the optimal concentration of Inkort 8MZ.VN for CT3 carbon steel in 3.5% NaCl solution, (ii) evaluate the corrosion protection efficiency of Inkort 8MZ.VN, while confirming the mechanism of protective film formation.

2. MATERIALS AND METHODS

2.1. Materials

The corrosion inhibitor Inkort 8MZ.VN used in this study has the following main technical specifications:

Table 1. *Main technical specifications of the Inkort 8MZ.VN corrosion inhibitor.*

No.	Technical specification	Unit	Value
1	Appearance	-	Transparent solution, dark pink (lotus) color
2	Density at 20 °C	g/cm³	1,3 ± 0,02
3	pH of 2% aqueous solution at 25 °C	-	10,3 - 11,4
4	Weight loss due to corrosion in 2% aqueous solution, for materials:		
	Copper, not more than	g/m²/day	0,2
	Aluminum, not more than		0,2
	Steel, not more than		0,2
5	Foaming characteristics		
	Foam volume, not more than	cm³	50,0
	Foam stability time, not more than	s	5,0
6	Rubber swelling, not more than	%	5,0

The working electrodes were fabricated from carbon steel (CT3) specimens, mechanically polished using 2000-grit abrasive paper and cleaned with ethanol/acetone prior to testing.

The inhibitor was used at various concentrations ranging from 0 to 2.5% in 3.5% NaCl solution.

The sample size for testing is 1*1*0,5 cm^3.

All tests were carried out at a temperature was 25 ± 0.5 °C.

2.2. Preparation methods

2.2.1. Experimental method (weight loss test)

The corrosion inhibition efficiency of Inkort 8MZ.VN was evaluated using the weight loss method, following the guidelines of ASTM G31.

Each specimen was weighed precisely and immersed in a 3.5% NaCl aqueous solution (simulated seawater) containing various concentrations of Inkort 8MZ.VN for 30 days at ambient temperature. After the exposure period, the samples were retrieved, cleaned, dried, and reweighed.

2.2.2. Electrochemical method

Electrochemical experiments were conducted using an Autolab PGSTAT 302N system equipped with a standard three-electrode configuration: a reference electrode (RE) of Ag/AgCl, a counter electrode (CE) made of platinum, and a working electrode (WE) composed of research alloys including: G steel, aluminum alloy A, copper alloy C1, and copper alloy C2. The exposed surface area of each working electrode was accurately fixed at (1*1 ± 0.01) cm^2. The Autolab system was operated via Nova 2.1.5 software. All measurement setup and data acquisition parameters were configured within this software environment. Experiments were performed at room temperature (25 ± 0.5 °C).

2.2.3. Scanning electron microscopy (SEM)

SEM analysis was employed to examine the surface morphology of the steel specimens after exposure to the corrosive environment. This method allows for high-resolution imaging of corrosion features. By comparing the surface conditions of uninhibited and inhibited samples, the physical effectiveness of the inhibitor can be visually confirmed. SEM also supports qualitative assessment of film uniformity.

2.2.4. Electrochemical impedance spectroscopy (EIS)

EIS was performed using an Autolab PGSTAT 302N potentiostat/galvanostat equipped with a Frequency Response Analyzer (FRA) module. A conventional three-electrode electrochemical cell was employed, consisting of a saturated Ag/AgCl reference electrode (RE), a platinum counter electrode (CE), and a carbon steel working electrode (WE) with an exposed surface area of (1*1 ± 0.01) cm².

3. RESULTS AND DISCUSSION

3.1. Electrochemical method

Table 2 showed that the absence of Inkort 8MZ.VN (sample M0), the corrosion potential (Ecorr) was observed at –0.610 V with a corresponding corrosion current density (Icorr) of 3.96×10^{-5} A. This high current density reflects rapid electrochemical degradation in the chloride-rich environment.

Upon increasing the concentration of Inkort:

- The corrosion current density decreased progressively.

- At 2% (sample M4), Icorr dropped dramatically to 5.32×10^{-9} A, corresponding to a corrosion rate of 0.00012 mm/year.

- The calculated inhibition efficiency at this concentration reached 99.99%, indicating near-complete surface protection.

***Table 2.** Summarizes the electrochemical parameters and inhibition performance.*

Sample	Inkort 8MZ.VN (%)	Ecorr (V)	Icorr (A)	Corrosion rate (mm/year)	Inhibition efficiency (%)
M0	0	-0.61016	3.96e-05	0.919	0
M1	0,5	-0.60607	3.34e-05	0.776	15.59
M2	1,0	-0.60511	2.71e-05	0.629	31.57
M3	1,5	-0.60381	2.52e-05	0.585	36.43
M4	2,0	-0.43326	5.32e-09	0.00012	99.98
M5	2,5	-0.47128	1.79e-09	4e-05	99.99

The Tafel plots, derived from linear sweep voltammetry (LSV) and presented in figure 1, demonstrate clear shifts in the electrochemical response upon the addition of the inhibitor at various concentrations. Comparing all Tafel curves, it could be found that they possessed a similar shape, indicating that Inkort 8MZ did not alter the anodic and cathodic reaction mechanisms of steel.

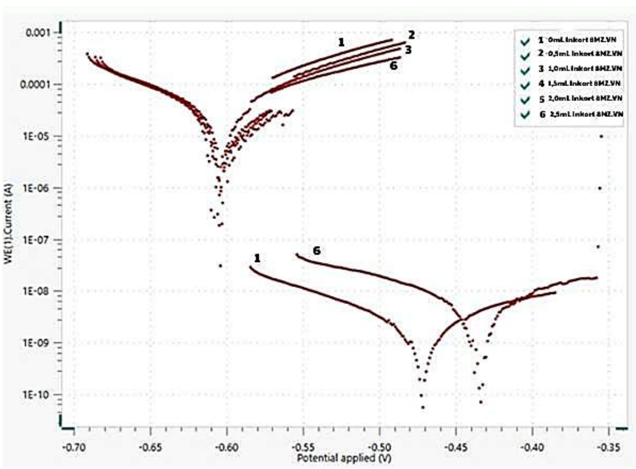


***Figure 1.** Tafel polarization curves of carbon steel in 3.5% NaCl solution with varying Inkort 8MZ.VN concentrations.*

Tafel analysis clearly confirms that Inkort 8MZ.VN is highly effective in inhibiting galvanic corrosion of carbon steel in saltwater environments when the potential shifts to the more negative side. Maximum efficiency is achieved at a concentration of 2%, beyond this concentration (2.5%), only a small improvement is achieved.

3.2. Weight loss test

The corrosion behavior of carbon steel in 3,5% NaCl solution, with and without the presence of the Inkort 8MZ.VN inhibitor was initially evaluated using the weight loss method. The results are summarized in table 3.

Over a 30-day immersion period, the uninhibited sample (M0) exhibited the highest corrosion rate of 1,73 $g \cdot m^{-2} \cdot day^{-1}$, indicating significant material degradation in the chloride-rich environment, upon the addition of Inkort 8MZ.VN, the corrosion rate decreased progressively with increasing inhibitor concentration.

At a concentration of 0,5% (M1), the corrosion rate decreased to 1,53 $g \cdot m^{-2} \cdot day^{-1}$, corresponding to an inhibition efficiency of 11.5%. Further increases in concentration to 1% (M2) and 1,5% (M3) improved the inhibition efficiencies to 19.2% and 34.6%, respectively. The most significant protection was observed at 2% (M4) and 2,5% (M5), where the corrosion rate dropped to only 0.20 $g \cdot m^{-2} \cdot day^{-1}$, yielding an inhibition efficiency of 88.5%. These results clearly demonstrate the concentration-dependent corrosion inhibition performance of Inkort 8MZ.VN. The significant reduction in corrosion rate, especially at higher concentrations, indicates the formation of a stable protective film.

This film acts as a physical barrier, limiting the diffusion of corrosive species (e.g., Cl^- ions) to the metal surface, thereby suppressing both anodic and cathodic reactions.

Table 3. *Corrosion rate and inhibition efficiency of carbon steel with different concentrations of Inkort 8MZ.VN in 3,5% NaCl solution.*

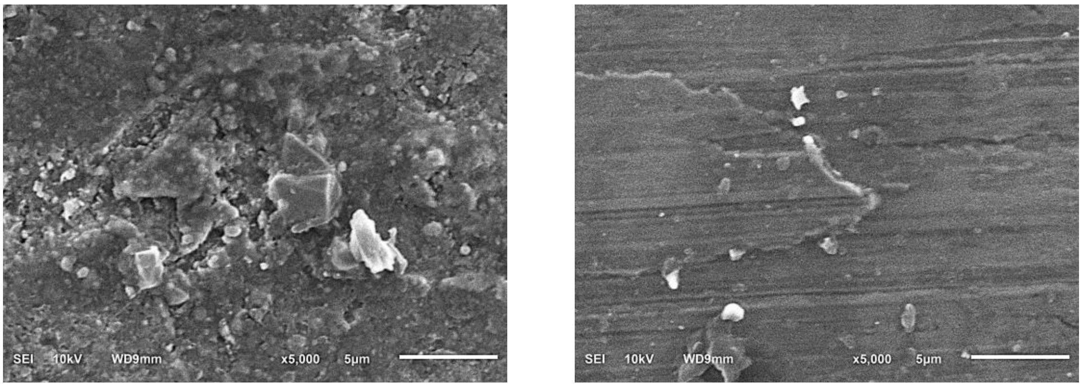
Sample	Inkort concentration (%)	Initial weight (g)	Final weight (g)	Weight loss (g)	Corrosion rate ($g/m^2/day$)	Inhibition efficiency (%)
M0	0	2,178	2,152	0,026	1,73	0
M1	0,5	2,228	2,205	0,023	1,53	11,5
M2	1,0	2,28	2,259	0,021	1,4	19,2
M3	1,5	2,689	2,672	0,017	1,13	34,6
M4	2,0	2,135	2,132	0,003	0,2	88,5
M5	2,5	2,288	2,285	0,003	0,2	88,5

3.3. Morphological observation

To further evaluate the protective performance of Inkort 8MZ.VN, the surface morphologies of carbon steel specimens after 30 days of immersion in 3,5% NaCl solution were examined using scanning electron microscopy (SEM). The micrographs are presented in figure 2.

Figure 2a shows the SEM image of the unprotected steel surface (blank sample, M0). A severely corroded and heterogeneous morphology is observed. The surface is covered with deep pits, cracks, and corrosion products, indicating extensive damage due to chloride attack in the saline environment.

In contrast, figure 2b displays the surface of the steel sample immersed in the same solution but supplemented with 2% of Inkort 8MZ.VN (sample M4). A compact, uniform, and largely intact surface morphology is evident. Only minor surface roughness and a thin passive film are visible, suggesting the effective formation of a protective barrier that inhibits further corrosive activity.



(a) Without inhibitor (M0). *(b) With 2% Inkort 8MZ.VN (M4).*

Figure 2. *SEM micrographs of the carbon steel surface after 30 days of 3,5% NaCl solution.*

3.4. Electrochemical impedance spectroscopy (EIS*)*

The Nyquist plots obtained for steel (CT3) immersed in 3.5% NaCl solution with and without the addition of 2% of Inkort 8MZ.VN is shown in figure 3.

For the uninhibited sample (0 ml), the Nyquist plot shows a relatively small semicircular diameter, corresponding to a low R_{ct} value, indicating that the CT3 steel was heavily corroded. In contrast, the inhibited sample (2% Inkort 8MZ.VN) shows a significant increase in the semicircular diameter, reflecting a significantly higher R_{ct} value.

This suggests that the inhibitor molecules were adsorbed onto the steel surface, hindering charge transfer and thus reducing the corrosion rate.

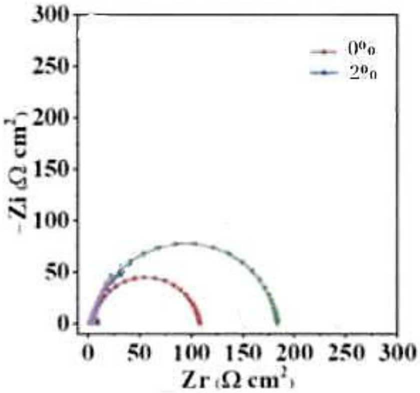


Figure 3. *Nyquist for CT3 steel in 3,5% NaCl with 0 and 2% of Inkort 8MZ.VN at 25 °C.*

The corrosion inhibition effect of adding 2% of Inkort 8MZ.VN is clearly demonstrated by the increase in R_{ct} 820 $\Omega \cdot cm^2$, while the double layer capacitance (C_{dl}) decreases, as inferred from the CPE parameters (Q and n). The decrease in C_{dl} is consistent with the displacement of water molecules and chloride ions by the inhibitor molecules at the metal/solution interface, forming a more protective and compact layer.

The calculated inhibition efficiency (IE%) from EIS at 2% is 81.7%, which is consistent with the efficiency obtained from Tafel polarography and mass loss measurements. In all three methods, the inhibitor at this concentration achieved high efficiency, confirming the reliability of the electrochemical data. The fitting parameters are summarized in table 4.

In figure 4, the impedance spectra were fitted to an equivalent electrical circuit model consisting of the solution resistance (R_s) in series with a parallel combination of charge transfer resistance (R_{ct}) and a constant phase element (CPE) representing the double-layer capacitance.

Table 4. *The EIS parameters of CT3 steel in 3,5% NaCl with 0 and 2% of Inkort 8MZ.VN at 25 ºC.*

Concentration (%)	R_s (Ω·cm²)	R_{ct} (Ω·cm²)	Q ($S \cdot s^n \cdot cm^{-2}$)	n	IE (%)
0	12.5	150	3.21E-5	0.88	—
2	11.8	820	1.45E-5	0.90	81.7

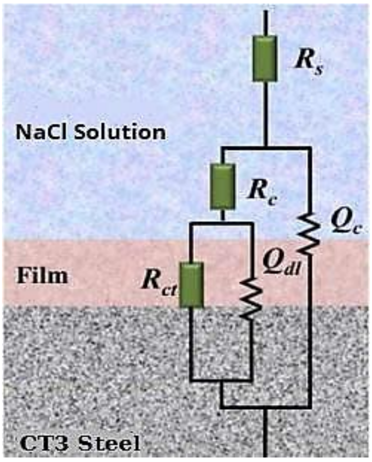


Figure 4. *The equivalent circuit used to fit EIS data.*

With the systematic results from the above evaluation methods, it can be concluded that performing EIS at the optimum inhibitor dosage (2%) is sufficient for characterizing the corrosion inhibition performance in this system, without requiring EIS measurements at lower concentrations. The complementary results from weight loss and potentiodynamic polarization methods adequately capture the inhibition trend across concentrations, while the EIS at the optimum point provides mechanistic insight into the interfacial behavior and protective film formation.

4. CONCLUSIONS

The corrosion behavior of CT3 carbon steel in 3.5% NaCl solution with and without Inkort 8MZ.VN was investigated, and the main findings are as follows:

- The optimal concentration of Inkort 8MZ.VN was determined to be 2%, achieving inhibition efficiency above 99% in 3.5% NaCl solution (equivalent to the salinity of seawater in Vietnamese coastal regions).
- The inhibition mechanism was confirmed to be the formation of a stable protective silicate film, as indicated by increased charge transfer resistance (R_{ct}) and reduced double-layer capacitance (C_{dl}) in the EIS results.

These results demonstrate that Inkort 8MZ.VN at its optimal concentration is an effective and relatively environmentally friendly corrosion inhibitor, suitable for application in the cooling systems of diesel generators operating in marine environments.

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TÓM TẮT

Đánh giá hiệu quả ức chế ăn mòn của Inkort 8MZ.VN ứng dụng trong hệ thống làm mát máy phát điện diesel hoạt động trong môi trường biển

Nghiên cứu này khảo sát hiệu suất ức chế ăn mòn của chất ức chế Inkort8MZ.VN trên thép cacbon CT3 trong dung dịch NaCl 3,5% (tương đương độ mặn của nước biển ở vùng biển Việt Nam). Hiệu suất ức chế tối ưu (> 99%) đạt được khi sử dụng 2% Inkort 8MZ.VN, bằng chứng là tốc độ ăn mòn giảm đáng kể, mật độ dòng điện anốt/catốt và tổng điện trở chống ăn mòn ($R_n = R_{film} + R_{ct}$) tăng hai bậc. EIS sử dụng mạch Randles mô phỏng đã xác nhận sự hình thành của một lớp màng bảo vệ (R_{film}) trên lớp kép, làm giảm C_{dl} và tăng R_{ct}. Những hiệu ứng này phù hợp với các quan sát về vi cấu trúc từ SEM. Kết quả chứng minh Inkort 8MZ.VN ở nồng độ tối ưu có hiệu quả bảo vệ chống lại sự ăn mòn do clorua gây ra trong hệ thống làm mát máy phát điện diesel khi hoạt động trong môi trường biển.

Từ khoá: Thép CT3; Chất ức chế ăn mòn; Inkort8MZ.VN; Ăn mòn trong dung dịch NaCl; Điện hóa.