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The Impact of Sulfur Compounds Functioning as Organic Pollutants on the Corrosion of Carbon Steel in Concentration Cells

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Abstract

Corrosion is a major challenge in the petroleum industry, influenced by internal fluid conditions and external factors. Concentration cell corrosion occurs when metals interact with solutions of varying concentrations, often exacerbated by sulfur-containing contaminants. This study explores the effects of mercaptoethanol (ME, C_2H_6OS), a sulfur compound commonly found in refinery effluents, on the corrosion behavior of carbon steel (CS) at different temperatures and concentrations. The findings highlight ME's strong influence on corrosion dynamics, demonstrating that both concentration and temperature are crucial factors. At 25 °C, the corrosion rate notably decreased from 5.594 gmd to 3.705 gmd as the ME concentration increased from 1 ml/l to 3 ml/l. Similarly, at 32 °C, while the rate dropped from 4.877 gmd to 4.502 gmd (ME increased 1 ml/l to 2 ml/l), it showed a slight increase to 4.701 gmd at 3 ml/l. Remarkably, at higher temperatures of 40 °C and 50 °C, the corrosion rate jumped from 6.954 gmd to an astonishing 16.267 gmd (ME increased from 1 ml/l to 2 ml/l) before declining to 4.002 gmd and 5.785 gmd at 3 ml/l, respectively. Additionally, the electrochemical potential of CS in the presence of mercaptoethanol shifted negatively with rising temperatures, indicating the formation of a protective surface film. This behavior contrasts with that observed with 0.1 N NaCl, where oxide films form as temperatures increase. These compelling findings emphasize the complex relationship between concentration, temperature, and corrosion mechanisms within concentration cells. These findings highlight mercaptoethanol's advantage over NaCl in mitigating galvanic corrosion in industrial applications.

Keywords: organic pollutant corrosion; Galvanic corrosion; carbon steel; concentration cell; mercaptoethanol.

تأثير المركّبات الكبريتية بوصفها ملوِّثات عضوية على تآكل الفولاذ الكربوني في خلايا التركيز

الخلاصة

يُعَدّ التآكل أحد التحديات الرئيسية في صناعة النفط، ويتأثر بظروف الموائع الداخلية والعوامل الخارجية المحيطة. ويحدث تآكل خلايا التركيز عندما تتفاعل المعادن مع محاليل تختلف في تراكيزها، وغالباً ما يزداد هذا التأثير بفعل الملوِّثات المحتوية على الكبريت. يتناول هذا البحث دراسة تأثير مركب ميركابتو إيثانول (ME, C_2H_6OS)، وهو أحد المركبات الكبريتية الشائعة في المياه الناتجة من نفايات المصافي النفطية، على سلوك تآكل الفولاذ الكربوني (CS) عند تراكيز ودرجات حرارة مختلفة.

أظهرت النتائج أن لمركّب الميركابتو إيثانول تأثيراً واضحاً في ديناميكيات التآكل، إذ تبيّن أن كلاً من التركيز ودرجة الحرارة عاملان حاسمان في تحديد معدل التآكل. عند درجة حرارة 25 °م انخفض معدل التآكل من 5.594 gmd إلى 3.705 gmd بزيادة تركيز ME من 1 مل/لتر إلى 3 مل/لتر. وبالمثل، عند 32 °م انخفض المعدل من 4.877 gmd إلى 4.502 gmd (عند زيادة ME من 1 إلى 2 مل/لتر)، لكنه ارتفع قليلاً إلى 4.701 gmd عند تركيز 3 مل/لتر.

وعند درجات حرارة أعلى، 40 °م و50 °م، ارتفع معدل التآكل بشكل ملحوظ من 6.954 gmd إلى 16.267 gmd (عند زيادة ME من 1 إلى 2 مل/لتر)، ثم انخفض إلى 4.002 gmd و5.785 gmd عند تركيز 3 مل/لتر على التوالي. كما أظهرت النتائج أن الجهد الكهروكيميائي للفولاذ الكربوني في وجود الميركابتو إيثانول يتحول نحو قيم سالبة مع ارتفاع درجات الحرارة، مما يشير إلى تكون طبقة سطحية واقية.

ويختلف هذا السلوك عن ما يحدث في حالة NaCl 0.1N، حيث تتشكل طبقات أوكسيدية مع ارتفاع درجات الحرارة. تؤكد هذه النتائج المتميزة العلاقة المعقدة بين التركيز ودرجة الحرارة وآليات التآكل في خلايا التركيز، وتُبرز هذه النتائج تفوق الميركابتو إيثانول على كلوريد الصوديوم في تخفيف التآكل الجلفاني في التطبيقات الصناعية.

1. Introduction

Corrosion is a big problem in the oil and gas industry. It causes financial losses, safety hazards, and environmental damage. It can happen at any stage of processing petroleum and natural gas and has devastating consequences for the world economy[1-3]. Researchers have extensively studied metal corrosion caused by corrosive organic or inorganic materials in solutions over the years due to its significant impact on the lifespan of the metals. When two different metals come in contact with each other in a corrosive environment (an electrolyte solution), galvanic corrosion occurs. The more reactive metal becomes an anode, and the less reactive metal becomes a cathode, which can occur due to the concentration difference of corrosive species known as concentration cells, as shown in Figure (1) [4-6]. The anodic metal erodes due to the path for ions to flow created by the electrolyte. Galvanic corrosion is impacted by various factors, including joint type, geometry, environmental process parameters, and the electrical potential of two metals[4,7]. Fortunately, there are several effective methods to mitigate this type of corrosion, these include isolating the two metals from each other, selecting similar materials or materials with similar electrical potentials, or adding a corrosion inhibitor[8-10].

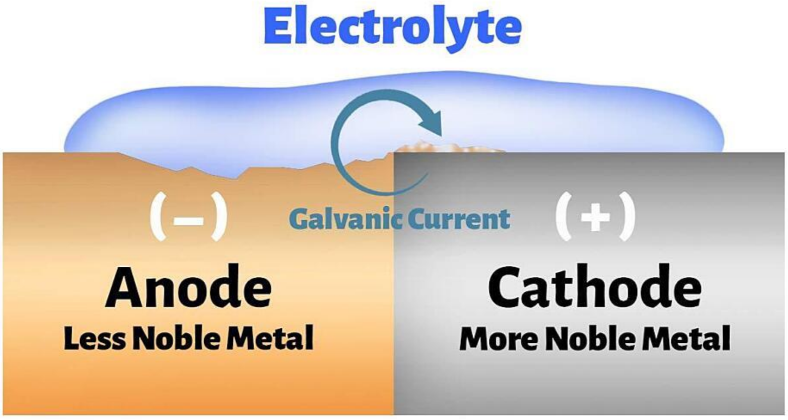

Fig. (1): Illustrated Galvanic Corrosion of dissimilar metals[11].

Carbon steels are commonly used in the oil and gas industry due to their low cost, satisfactory corrosion resistance, and excellent machining performance. However, exposure to different metals in various operating conditions can cause corrosion. Situations such as using brass fittings with carbon steel or galvanized steel pipes, welding of steel with brass, and practical applications of brass in electrical circuits can lead to galvanic currents that result in an accelerated corrosion rate of carbon steel [6, 12]. Significant research has been carried out to fully understand the behavior and mechanism of galvanic corrosion between alloy/stainless steel and carbon steel in a multitude of environments [3-6, 13]. In this study, the corrosion behavior of carbon steel was investigated using mercaptoethanol (ME) as a sulfur compound under various temperature and concentration conditions. The study revealed that the presence of ME led to a noteworthy increase in the corrosion rate of carbon steel. This phenomenon was attributed to the formation of concentration cells, intensifying the corrosion process. Furthermore, the study highlighted the growing prevalence of galvanic corrosion with rising ME concentrations and temperatures. This type of corrosion, driven by electrochemical interactions between dissimilar metals, became more pronounced as conditions favored its occurrence. Notably, the research also made an interesting observation regarding the severity of carbon steel corrosion. The corrosion process was found to be less severe in the ME terminal (where ME served as the corrosive agent) as compared to the NaCl solution terminal (where sodium chloride was the corrosive agent). This suggests that ME-induced corrosion may have distinct characteristics or mechanisms compared to traditional chloride-induced corrosion processes.

2. Materials and Methods

2.1. Materials

Pure sodium chloride (NaCl) was selected as the salt for preparing electrolyte solutions, ensuring consistent ionic strength across all tests. Mercaptoethanol (ME), with a molecular weight of 78.13 g/mol and a certified purity of 99%, was utilized as the sulfur-containing compound, sourced from a reputable chemical supplier to ensure the reliability of the results. Distilled water was used in all experiments to minimize the influence of impurities. Key properties of the water included a conductivity of 6.63 μS, a pH of 6.86, and an oxygen solubility of 6.08 ppm, all measured at a controlled laboratory temperature of 27°C to maintain consistent environmental conditions. The carbon steel samples used in the study underwent thorough characterization to determine their precise chemical composition, accomplished using advanced X-ray diffraction (XRD) techniques at the Materials Research Center, affiliated with the Ministry of Science and Technology. The resulting elemental composition data were compiled and are presented in Table (1). These analyses were essential for understanding the impact of the steel's material properties on its corrosion behavior under the tested conditions.

Table (1): Chemical composition of carbon steel used. [14].

sample	**Mg**	**Al**	**Si**	**P**	**S**	**Ti**	**V**	**Cr**	**Mn**
(Wt.% %)	0.020	0.0044	0.0016	0.00098	0.0020	0.0016	0.0014	0.1248	0.472
sample	**Zn**	**As**	**Zr**	**Nb**	**Mo**	**Ag**	**Cd**	**Sn**	**Sb**
(Wt.% %)	0.0060	0.00017	0.013	0.0037	0.183	0.00061	0.00063	0.00099	0.0010
sample	**Co**	**Ni**	**Cu**						
(Wt.% %)	0.425	0.0022	0.0519						

The study utilized solutions comprising NaCl and Mercaptoethanol (C_2H_6OS) in a 0.1N NaCl medium. Mercaptoethanol, a sulfur-containing compound, was tested at varying concentrations of 0.1%, 0.2%, and 0.3% (v/v) to investigate its effects on corrosion behavior. The carbon steel specimens were precision press-cut into square coupons with dimensions of 40 mm × 40 mm, providing a total exposed surface area of 1600 mm^2. To facilitate immersion and ensure stability during testing, each specimen was perforated and securely fastened using fine screws. The diameter of the perforation was carefully minimized to avoid a significant impact on the overall exposed surface area. For surface preparation, ethanol was used to clean the specimens, ensuring the removal of contaminants. This cleaning step was crucial to maintain consistency across experiments and ensure accurate measurement of corrosion effects.

2.2. Experimental work

The experimental work aimed to evaluate the free corrosion rate and galvanic corrosion, including the effects of concentration cells on carbon steel (CS) specimens immersed in NaCl solutions containing organic pollutants. The pollutant under investigation was Mercaptoethanol (C_2H_6OS), a sulfur-containing compound, studied at varying concentrations. The experiments were designed to assess the influence of Mercaptoethanol concentrations on carbon steel under controlled temperatures of 25°C, 32°C, 40°C, and 50°C. The concentrations of Mercaptoethanol were varied from 0.1% to 0.3% (v/v) within a 0.1N NaCl solution. Additionally, the role of dissolved oxygen in the electrolyte solution was measured. To prepare for each test, the electrode specimens underwent a meticulous surface preparation process. Initially, they were abraded with emery papers of progressively finer grades, specifically 120, 220, 400, and 2000 grit, to achieve a uniform surface finish. Following this, the specimens were brushed under running tap water using a plastic brush to remove the loose part residual corrosion products. Then, thoroughly rinsed with distilled water and dried with a clean tissue. Subsequently, the specimens were briefly immersed in ethanol for 30 seconds and dried in an electric oven at 80°C for 3 minutes.

Finally, the specimens were stored in a desiccator containing high-activity silica gel to prevent contamination until testing. After that they were weighed with high precision using an analytical balance before commencing the corrosion tests. The NaCl solution was heated to the desired temperature, after which the specimens were connected using a wire to measure galvanic currents with a Zero Resistance Ammeter (ZRA). One specimen was connected to the positive (+ve) terminal, while the other was attached to the negative (-ve) terminal. For consistent handling, the coupon was mounted on a display board using a small screw, though its contribution to the system was negligible. During each experimental run, the galvanic potential variations were monitored using a Standard Calomel Electrode (SCE) bridge. Galvanic currents and potentials of the coupled specimens were recorded continuously for 2 hours while immersed in the electrolyte solution. After each test, the specimens were cleaned and weighed again using a highly sensitive SAUTER balance with an accuracy of 0.1 mg. The corrosion rate for the specimens, calculated in grams per square meter per day (gmd), was determined using the following equation:

$$CR = \Delta W / A \times t \qquad \ldots (1.1)$$

The weight loss (ΔW) in grams is calculated based on the exposed area (A) in m² and the exposure time (t). Figure (2) shows the experimental apparatus used for testing free and galvanic corrosion.

Fig. (2): Displays the equipment utilized to investigate free and galvanic corrosion.

3. Results and Discussion

3.1. Free Corrosion of CS in Mercaptoethanol (ME)

This study introduces a novel weight-loss technique to evaluate the corrosion rate and concentration cell corrosion of commercial carbon steel (CS) in the presence of the sulfur compound mercaptoethanol (C_2H_6OS). The study was performed under controlled conditions, varying both the temperature and the concentration of mercaptoethanol in a 0.1N NaCl solution. Table (2) presents the average open-circuit potential (OCP) values recorded after five minutes of free corrosion of carbon steel at different temperatures and concentrations of C_2H_6OS. A series of experiments was conducted to measure the corrosion rate of carbon steel in solutions with varying concentrations of mercaptoethanol. The results indicated that the corrosion rate remained relatively low, even when the metal was exposed to mercaptoethanol solutions at different temperatures. This observation can be attributed to the solution's inherently low thermal conductivity and the lack of additional salts, which could otherwise enhance corrosive activity.

Table (2): Shows the free corrosion of CS in different C_2H_6OS concentrations (per litter of NaCl solution) and temperatures (Average values of OCP for 5 mins).

		OCP (volt)	
T, °C	**1 ml C_2H_6OS**	**2 ml C_2H_6OS**	**3 ml C_2H_6OS**
25	-0.393	-0.426	-0.503
32	-0.578	-0.587	-0.586
40	-0.628	-0.622	-0.702
50	-0.668	-0.656	-0.685

Figure (3) illustrates the variation in open-circuit potential (OCP) of carbon steel (CS) in a 0.1N NaCl solution as a function of temperature and varying concentrations of mercaptoethanol

(C_2H_6OS). The results show that the corrosion potential decreases with rising temperature for solutions containing 1 mL and 2 mL of C_2H_6OS (per litter of NaCl solution), both concentrations demonstrating similar behavior. However, the solution with 3 mL of C_2H_6OS reveals a notably more negative corrosion potential, suggesting the formation of a thicker or more robust surface film on the metal substrate. As the temperature increases from 25°C to 40°C, the corrosion potential becomes progressively more negative across all tested concentrations of C_2H_6OS, indicating an increased susceptibility to corrosive processes or changes in surface film characteristics. Beyond 40°C, the corrosion potential begins to shift toward more positive values, eventually aligning with the potential observed for the 1 mL and 2 mL solutions at 50°C. This behavior contrasts with the trend observed in a pure 0.1N NaCl solution, where the corrosion potential consistently decreases with rising temperature, suggesting the formation of an oxide film that passivates the metal surface under these conditions. These findings emphasize the effects of C_2H_6OS concentration and temperature on the electrochemical behavior of carbon steel, with higher concentrations of the sulfur compound resulting in a distinct surface film dynamic that sets it apart from the behavior in NaCl-only solutions.

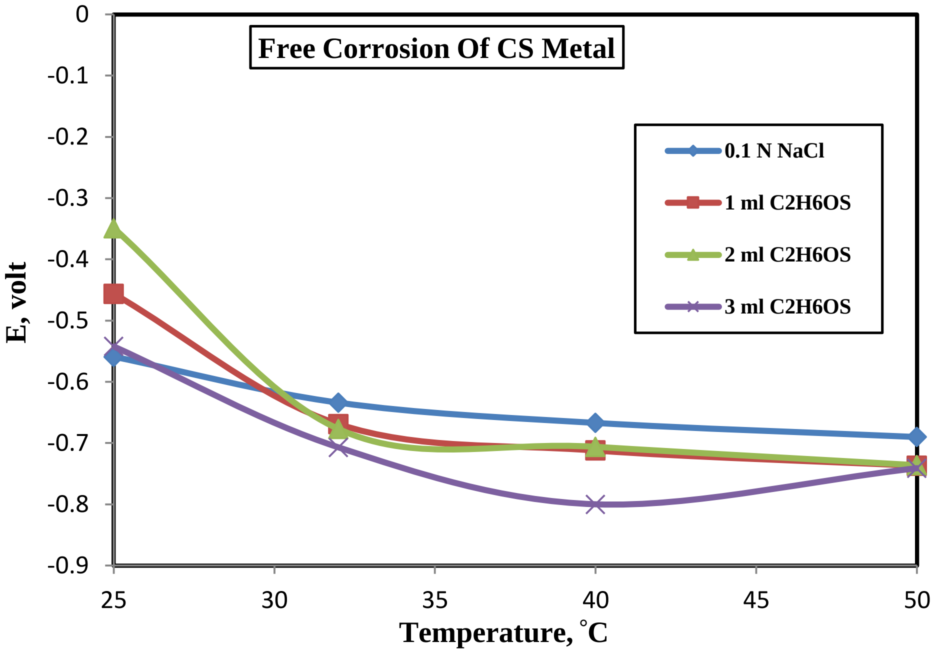

Fig. (3): The Corrosion potential of CS (E) with temperature in salt and different ME concentration solutions (per litter of NaCl solution).

3.2. Galvanic Corrosion in Concentration Cell by ME

The experiments examining the galvanic effects of mercaptoethanol (ME) in a concentration cell demonstrated a significant increase in the corrosion rate of carbon steel (CS) under the specified conditions. Both galvanic corrosion potential and galvanic current were measured during these experiments. The trends in corrosion potential over time for two CS specimens are presented in Figures (4) to (9). The specimens were coupled and immersed in different solutions: one in a 0.1 N NaCl solution and the other in an ME solution with concentrations ranging from 1 mL to 3 mL. To further evaluate the behavior of the galvanic current within the concentration cell, the study included a range of temperatures: 25°C, 32°C, 40°C, and 50°C. Figures (4) to (6) show that the corrosion potential initially starts at relatively high values before declining toward more negative values. This behavior is attributed to the clean surface directly exposed to the oxidizer, followed by the formation of an oxide film. Over time, the film undergoes reductive dissolution, leading to a decline in corrosion potential. This observation aligns with the findings of Hussein et al. [15]. In Figure (5), it is evident that the corrosion potential for both terminals begins with negative values, indicating active metal surfaces. However, the potential quickly shifts in a positive direction, reflecting the formation and repair of a transient protective film. This protective mechanism, however, is short-lived. After approximately 1 minute for the 1 mL C_2H_6OS solution and 2.5 minutes for the 0.1 N NaCl solution, the potential begins to oscillate sharply, signaling the onset of pitting corrosion, as also observed by prior studies [16]. Generally, the potential of Specimen 1 (S1), submerged in the NaCl solution, remains higher than that of Specimen 2 (S2), immersed in the ME solution. This suggests that the presence of the sulfur compound (ME) reduces the corrosion potential. Furthermore, Figures (5) to (7) illustrate that the corrosion potential stabilizes more quickly with increasing concentrations of C_2H_6OS and elevated temperatures. It is also notable that the potentials of coupled electrodes are closer together compared to their free corrosion open-circuit potentials, indicating the influence of galvanic coupling. The effect of temperature on potential behavior is generally subtle, except at 50°C, where the potentials of the two terminals become comparable, indicating a significant shift in corrosion dynamics at elevated temperatures.

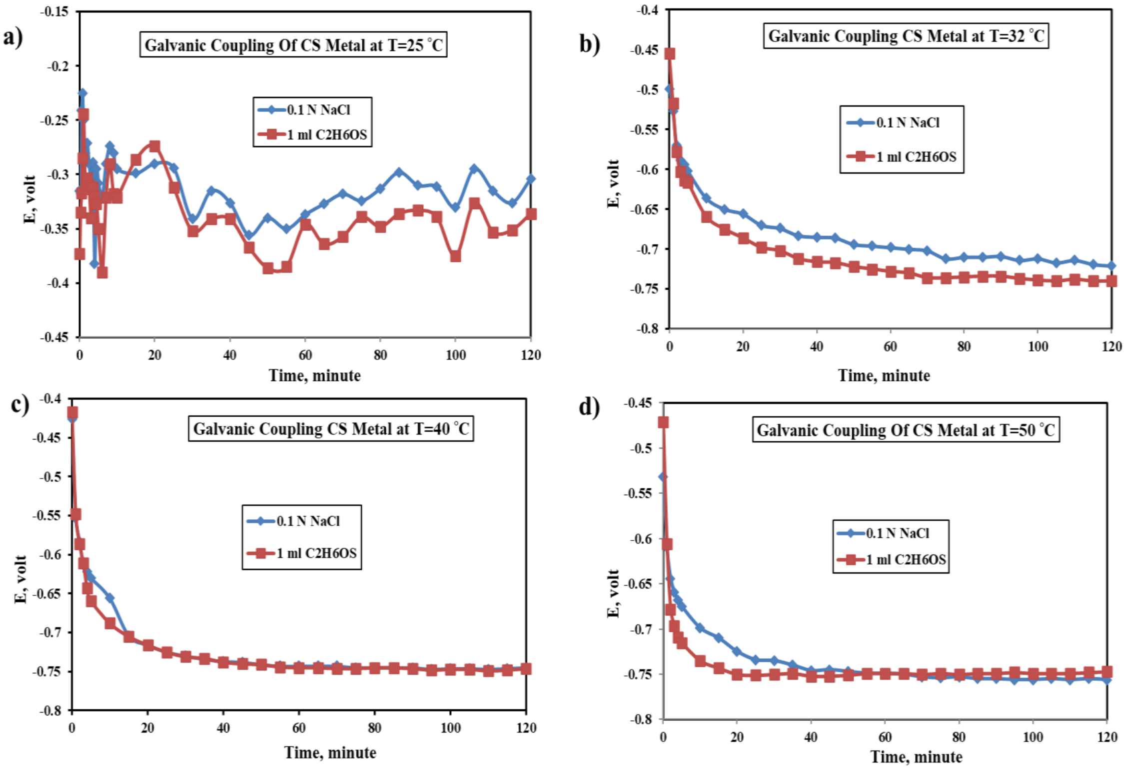

Fig. (4): Corrosion potential vs. time of CS couple in 0.1 N NaCl with 1 ml C_2H_6OS solution and from a: 25˚C, b: 32˚C, c: 40˚C, d: 50˚C.

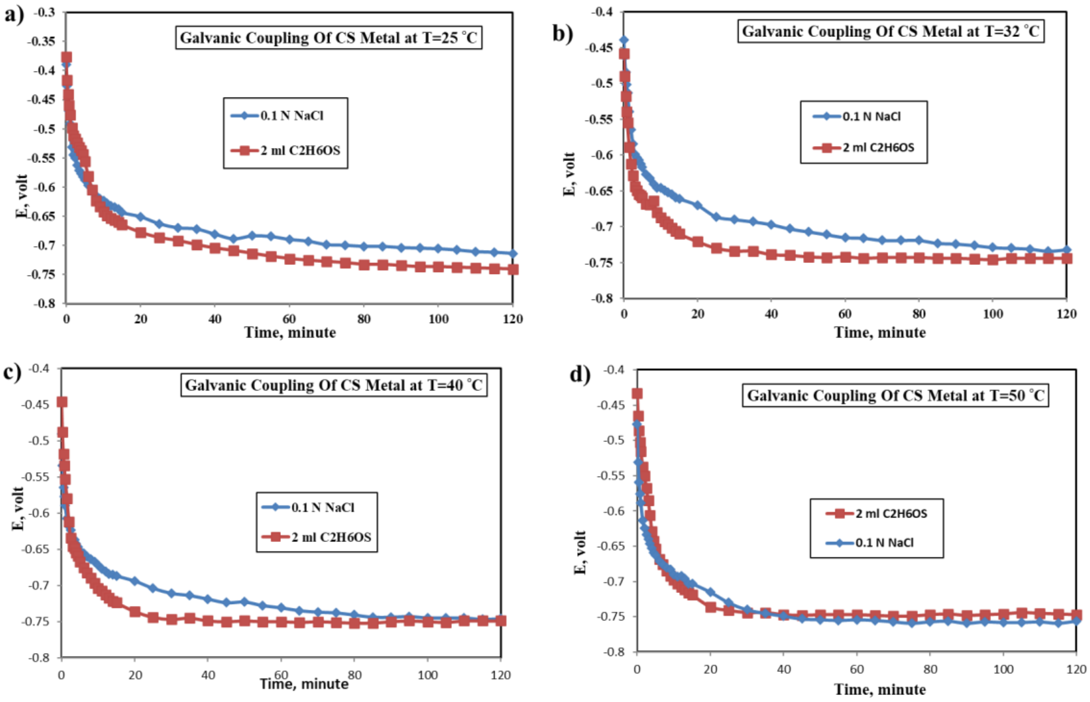

Fig. (5): Corrosion potential vs. time of CS couple in 0.1 N NaCl with 2 ml C_2H_6OS solution and from a: 25˚C, b: 32˚C, c: 40˚C, d: 50˚C.

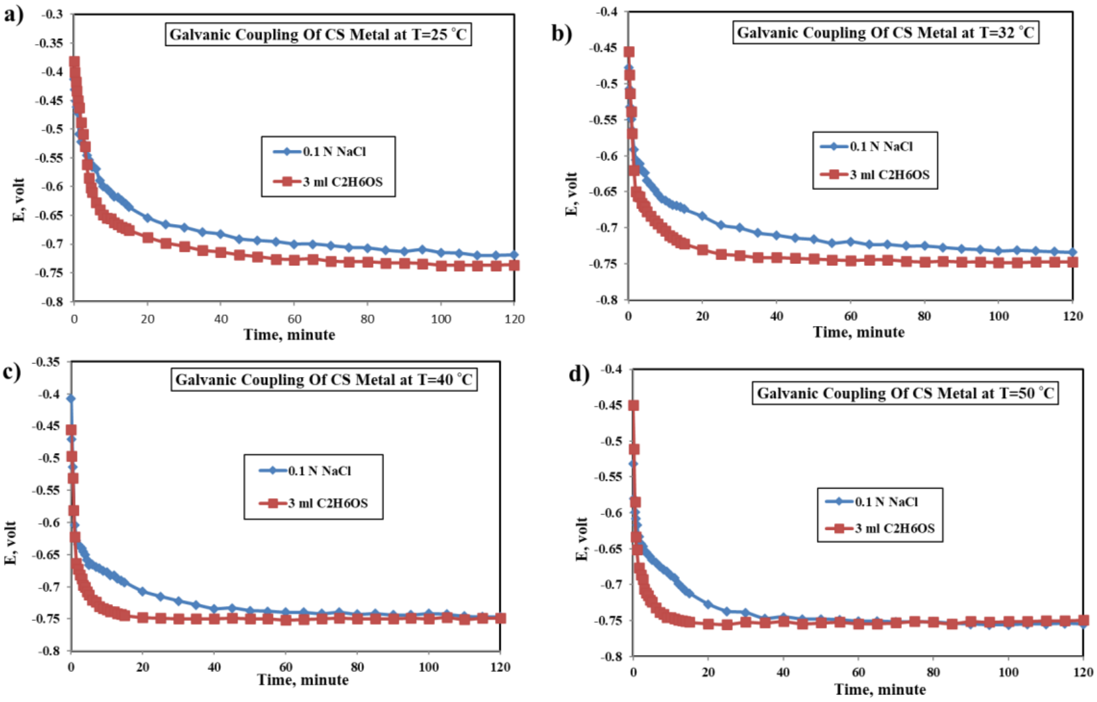

Fig. (6): Corrosion potential vs. time of CS couple in 0.1 N NaCl with 3 ml C_2H_6OS solution and from a: 25˚C, b: 32˚C, c: 40˚C, d: 50˚C.

The corrosion potential of CS in solutions containing 1, 2, and 3 ml of C_2H_6OS over time is shown in Figures (7) to (9). The data demonstrates that when the temperature rises, the corrosion potential shifts towards negative values before stabilizing at a constant value of -0.75 volts across all solutions. It is worth noting that in the 0.1 N NaCl solution, the corrosion potential decreases as the temperature increases. At 50°C, it becomes more negative than in the C_2H_6OS solutions. Furthermore, in open systems, the corrosion potential decreases at high temperatures. The effect of temperature is intricate due to the increase in oxygen diffusivity and decrease in solubility with a temperature rise. [17], [18].

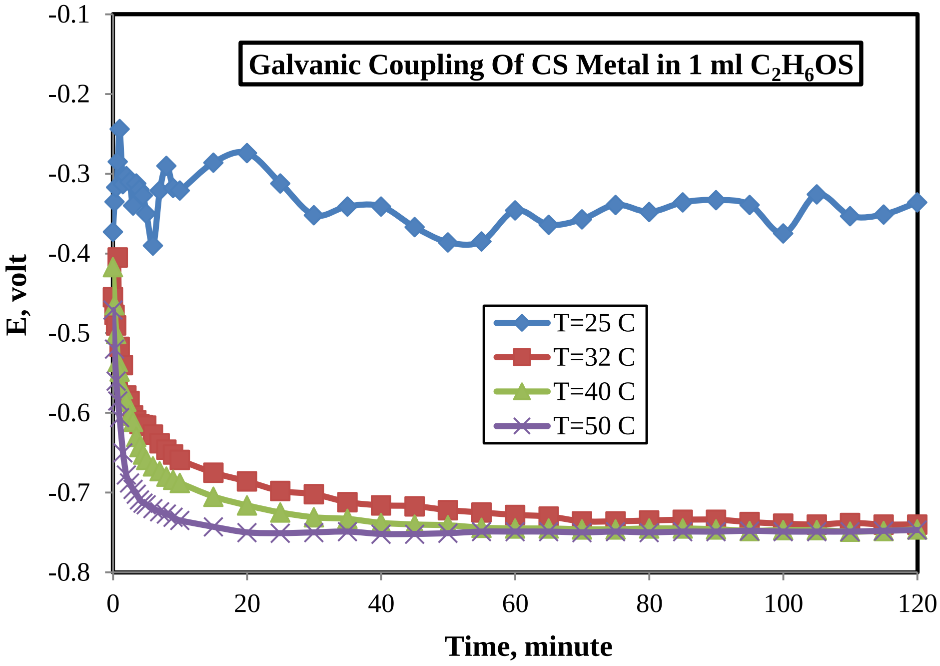

Fig. (7): Corrosion potential vs. time of CS couple between 1 ml C2H6OS solution and 0.1 N NaCl solution at different temperatures.

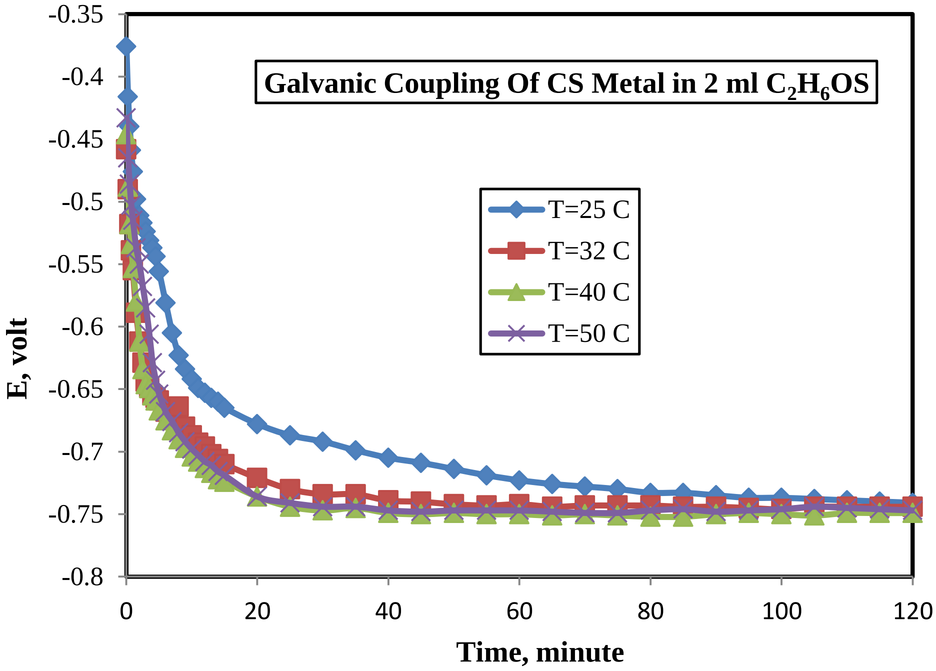

Fig. (8): Corrosion potential vs. time of the CS couple between 2 ml C_2H_6OS solution and 0.1 N NaCl solution at different temperatures.

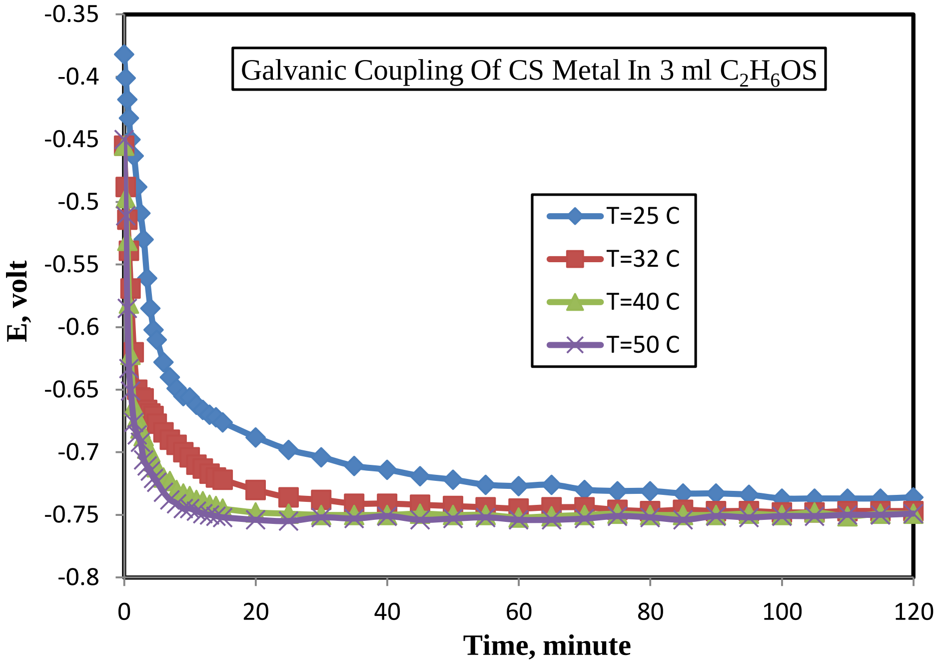

Fig. (9): Corrosion potential vs. time of the CS couple between 3 ml C_2H_6OS solution and 0.1 N NaCl solution at different temperatures.

3.3. Galvanic current

To determine the galvanic current, connect Sp.1 (NaCl solution) to the positive terminal and Sp.2 (C_2H_6OS solution) to the negative terminal of the Zero Resistance Ammeter (ZRA). Fiures. (10) to (12) demonstrate the variation of galvanic current over time at different temperatures for solutions containing 1 mL, 2 mL, and 3 mL of C_2H_6OS. The currents exhibit opposite directions in Figure (10) for 1 ml ME concentration. At 25, 32, and 40 °C, the temperature initially rises and then decreases until it reaches a steady state value. However, at 50 °C, the current initially starts negatively, then moves towards positive values, and subsequently decreases slightly towards negative values after 15 minutes. Generally, a higher temperature leads to a lower galvanic current. In Figure (11), at 2 ml ME, the galvanic current for T= 25 and 50 °C starts negatively and turns positive, stabilizing at 25 °C and returning to negative at 50 °C. At 32 and 40 °C, the currents start with positive and negative values, respectively, moving towards positive values and gradually decreasing towards negative values over time. A higher temperature generally results in a lower galvanic current. In Figure (11), all temperatures' galvanic currents start negatively, moving towards positive values of up to 10.6 µA at 50°C and gradually decrease back to negative over time. The different directions of currents in Figures (10) and (11) in 1 and 2 ml of ME can be attributed to a convergence in the corrosion rate between the specimens, and because of the convergence of pH values between solvents.

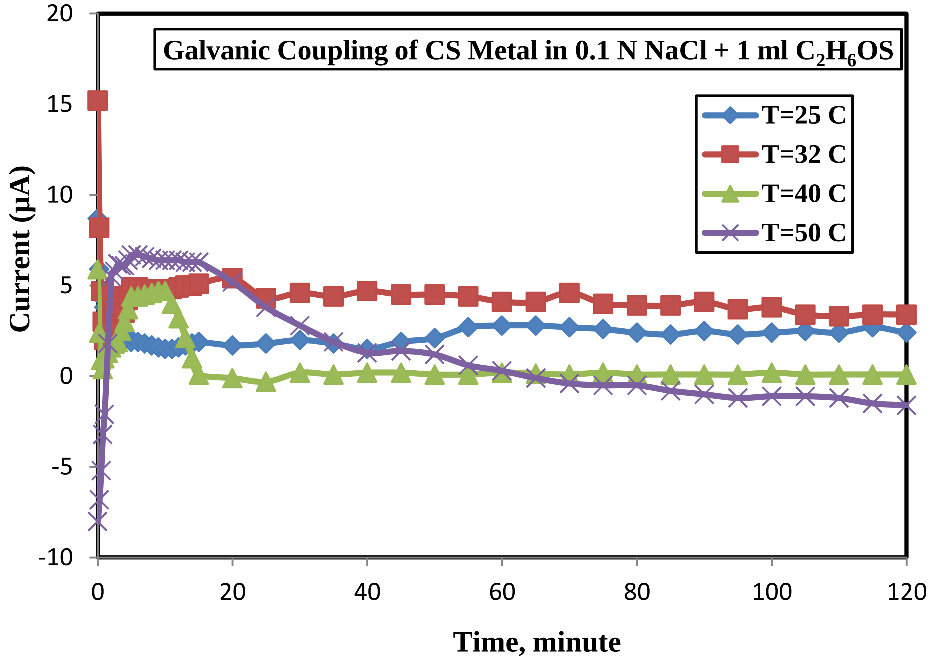

Fig. (10): Galvanic Current vs. time for CS couple in 0.1 N NaCl with 1 ml C_2H_6OS solution and different temperatures.

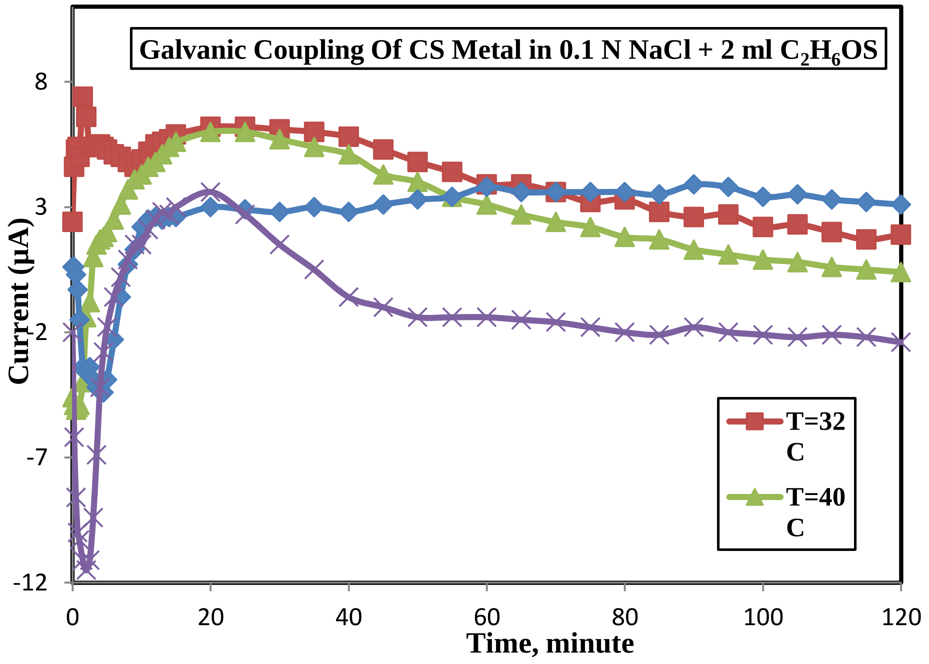

Fig. (11): Galvanic Current vs. time for CS couple in 0.1 N NaCl with 2 ml C_2H_6OS solution and different temperatures.

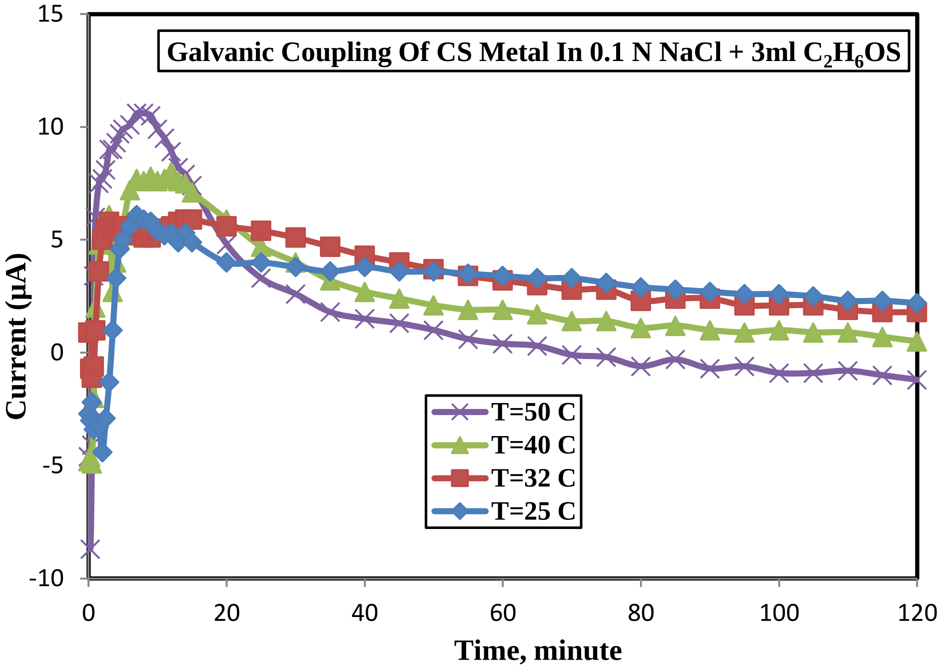

Fig. (12): Galvanic Current vs. time for CS couple in 0.1 N NaCl with 3 ml C_2H_6OS solution and different temperatures.

Figures (13 a, b, c, and d) display the galvanic current variation of the CS couple over time in different solutions of C_2H_6OS at temperatures of 25, 32, 40, and 50 °C. These figures indicate a difference in the direction of currents during the initial minutes of the experiment, followed by a settling into a consistent trend for different concentrations at a constant temperature. The difference in corrosion rates between the two specimens may be due to variations in temperature and concentration. At 25 °C, the corrosion rate of the specimens decreases with an increase in ME concentration. The corrosion rate decreases for metals at a 2 ml ME concentration but increases at a 3 ml ME concentration at 32 °C. Furthermore, at temperatures of 40 °C and 50 °C, the corrosion rate increases at a 2 ml ME concentration but decreases at a 3 ml ME concentration. This increase and decrease in the corrosion rate can be attributed to the effect of the concentration of the oxidizing substance. The addition of oxidizers may increase or not affect the corrosion rate, or a complex behavior may be observed[17]. The Fe-18Cr-8Ni stainless steel has a low corrosion rate in diluted sulfuric acid. The corrosion rate increases with concentration until it reaches a maximum and then decreases with further concentration increase [19].

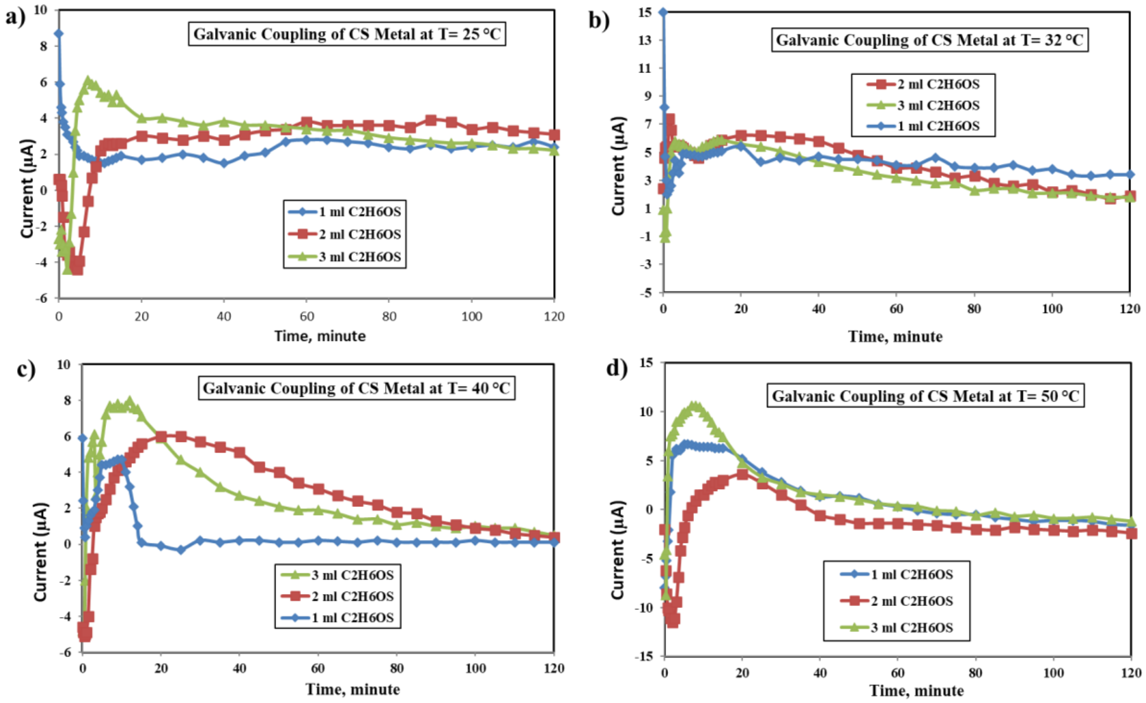

Fig. (13): Galvanic Current vs. time for CS couple in different concentrations of C_2H_6OS and 0.1 N NaCl at different temperatures (25 °C, 32°C,40°C, and 50°C).

Table (3) presents the corrosion rates in (gmd) of carbon steel (CS) specimens under galvanic coupling conditions: one immersed in 0.1N NaCl only (Sp.1) and the other in 0.1N NaCl mixed with 1, 2, or 3 mL of mercaptoethanol (C_2H_6OS) (Sp.2) at temperatures of 25°C, 32°C, 40°C, and 50°C, over 2 hours. The results indicate that Sp.1 consistently exhibits a higher corrosion rate compared to Sp.2 across all tested conditions. Figures (13 a to d), which depict the galvanic corrosion potential trends for the two specimens, further substantiate this observation. The data highlights that the addition of C_2H_6OS to the NaCl solution reduces the corrosion rate of carbon steel more effectively than under free corrosion conditions. This reduction in corrosion rate can be attributed to the influence of mercaptoethanol, which likely affects the electrochemical reactions occurring at the metal surface. During the corrosion process, multiple electrochemical reactions are involved. These include the oxidation of iron, the reduction of oxygen, and the interaction of iron with sulfur species present in the solution.

Table (3): Corrosion rate of carbon steel specimens coupled in different concentrations and temperatures.

T, ˚C	CR (gmd) **Coupling in 1st** Solution		**Coupling 2nd Solution**		**Coupling in the 3rd solution**	
	Sp.1 (0.1 N NaCl)	**Sp.2 (1 ml C_2H_6OS)**	**Sp.1 (0.1 N NaCl)**	**Sp.2 (2 ml C_2H_6OS)**	**Sp.1 (0.1 N NaCl)**	**Sp.2 (3 ml C_2H_6OS)**
25	8.948	5.594	7.829	5.389	5.892	3.705
32	8.317	4.877	7.084	4.502	10.980	4.701
40	9.754	7.218	13.130	10.193	8.522	4.002
50	11.017	6.954	19.164	16.267	9.942	5.785

4. Conclusions

This study investigated both free and galvanic corrosion of carbon steel (CS) materials under concentration cell conditions with the sulfur compound mercaptoethanol (ME, C2H6OS) across various concentrations and temperatures. The results show that the 3 ml ME solution exhibited a more negative potential, indicating the formation of a thicker surface film. All ME solutions displayed increasingly negative potential from 25 to 40 °C, returning to similar levels at 50 °C, whereas in 0.1 N NaCl, the potential decreased with rising temperature, suggesting oxide film formation. At 25 °C, the corrosion rate (C.R.) decreased with increasing ME concentration from 1 ml/l to 3 ml/l (5.594 to 3.705 gmd). At 32 °C, a similar decrease occurred from 4.877 to 4.502 gmd between 1 ml/l and 2 ml/l ME, followed by a slight increase to 4.701 gmd at 3 ml/l. At higher temperatures (40 °C and 50 °C), the C.R. initially increased with ME concentration from 1 ml/l to 2 ml/l (6.954 to 16.267 gmd) before declining to 4.002 and 5.785 gmd at 3 ml/l, respectively. In galvanic corrosion scenarios, the C.R. was consistently lower in ME solutions compared to NaCl solutions, with the potential of CS in ME being more negative by approximately 8.1% than in 0.1 N NaCl. These results highlight the nuanced interplay between temperature, concentration, and corrosion dynamics in concentration cells, providing valuable insights for developing effective inSuzan J. Abur contributed to data collection and/or processing, data/statistical analysis, and data interpretation.

Author Contribution Statement: Suzan T. Abbas contributed to data processing, data analysis, and data interpretation. Sahir M. Al-Zubaidi contributed to research design, data analysis, literature review, drafting the manuscript, and revision and proofreading. Basim O. Hasan contributed to conception of the study, data analysis, and revision and proofreading. All authors have read and approved the final version of the manuscript.

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