Corrosion behavior of carbon steel in a post-combustion CO$_2$ capture system containing sodium sulfide as a contaminant

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Abstract
Heat-stable salts are generally believed to increase the corrosion rate of metals in CO$_2$ capture systems but a few of them have shown inhibitive behaviors under certain experimental conditions. This paper presents a comprehensive evaluation on the effect of sodium sulfide found as a contaminant on the corrosion behavior of carbon steel in an amine-based CO$_2$ capture technology. Electrochemical test methods, weight loss measurements and surface analytical techniques were employed to assess the influence of sulfide in stagnant CO$_2$-purged amine solutions at 50 °C. Sodium sulfide exhibited two characteristic and opposite effects on the corrosion behavior of carbon steel and these effects depended largely on the salt concentrations. Low sulfide concentration forms a thin FeS corrosion film which inhibits the corrosion process proportional to the carbon steel surface coverage. This film does not permit the movement of electrons needed to activate cathodic processes. On the other hand, the high sulfide concentration forms a film with increased surface area on the carbon steel surface which encourages the movement of electrons on the surface and allowing cathodic processes to occur, hence, increasing the corrosion rate. Time-dependent corrosion studies were also carried out with respect to sulfide concentration and temperature. For the addition of 0.05 M and 0.1 M sulfide, the inhibition efficiency of the salt decreased from 89.1% and 75.0% to 82.4% and 68.6%, respectively, after 7 and 14 days immersion. When temperature was increased to 80 °C, the inhibition efficiency decreased from 89.1% to 48.9% after 7 days immersion and 82.4% to 46.1% after 14 days immersion.

Keywords
Carbon steel, heat stable salts, sulfide, polarization, weight loss

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**Introduction**

Corrosion in CO\textsubscript{2} capture units is one of the most severe operational challenges affecting safety and process economics leading to unexpected impediments and downtime, production loss and eventually, fatalities [1-3]. Many research works have been directed towards the preference, efficiency and prospects of a number of single and blended amine solutions [4-14], along with enhancement of operations [15-21]. Furthermore, CO\textsubscript{2}, O\textsubscript{2}, and H\textsubscript{2}O have been the most studied components of a typical flue gas composition with established information on their effects in amine-based carbon steel corrosion whereas, the effects of other flue gas components (such as sulfur oxide, SO\textsubscript{x} and nitrogen oxides, NO\textsubscript{x}) have been rarely espied. One of the most important classifications of compounds formed from SO\textsubscript{x} and NO\textsubscript{x} are called heat-stable salts (HSSs). These HSSs are formed in the capture process when acids stronger than CO\textsubscript{2} react with the amine solution. The acids can either be formed directly from flue gas components or from amine degradation products. The HSSs have attracted research attention due to their non-regenerable nature during the regeneration step of the capture process, thereby accumulating in the amine solution throughout the capture unit. It is therefore pertinent to identify and establish effects of compounds formed from other flue gas components on carbon steel corrosion in CO\textsubscript{2} capture systems. From our previous experiments, we discussed the effects of sodium sulfate and sodium sulfite [22], as well as comparing the effects of sodium sulfate with sodium sulfide in a capture system [23] but our reports for the sulfide were restricted by the scope of the research. Therefore, it became necessary to outline a systematic report that will evaluate the effect of the salt with respect to its concentration and the impact of some operational parameters, such as temperature, etc.

A few researchers have suggested that the presence of sulfide could either accelerate or inhibit carbon steel corrosion depending on the experimental conditions. Sulfide has been generally reported to strongly increase corrosion rate of iron by causing an increase in both the iron dissolution reaction and hydrogen evolution reaction [24-30]. It has also been involved in some strong inhibition actions when studied under some special conditions [30-34]. Some of the special conditions reported are: low sulfide concentration, immersion time $\geq$ 2 hours, and pH range of 3-5. The inhibitive actions were credited to the formation of iron sulfide (FeS) scale [35, 36].

**Experimental**

**Materials**
Carbon steel Q235 was selected as the corrosion specimen. Carbon steel finds wide application in the construction of the amine-based CO\textsubscript{2} capture plants [2, 37]. Its chemical composition is shown in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>0.23</td>
<td>0.79</td>
<td>0.02</td>
<td>0.03</td>
<td>0.29</td>
<td>0.20</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

The working electrode for the electrochemical measurements was embedded in epoxy resin with an area of 1.0 cm\textsuperscript{2} exposed while the coupons for weight loss measurements and surface analysis (SEM/EDS, XRD and XPS) were rectangular in shape with a total surface area
of 5.2 cm². Prior to subjection to electrochemical tests, weight loss measurements, and surface analytical tests, the surfaces were progressively polished with silicon carbide abrasive paper up to 1000, 2000 and 2000 grit, respectively, washed with distilled water, cleaned with ethanol, and finally dried with warm air.

The electrolyte solution was made up of MDEA with a concentration of 50% by weight which was prepared from a 99% MDEA reagent and distilled water. The introduced additive was sodium sulfide (Na₂S) (which was of industrial grade with concentrations above 97%). Before each experiment, the gas mixture (12% CO₂ + 6% O₂, with N₂ as the balance gas) was purged into the test solution at an experimental temperature of 50 °C to simulate a typical absorber condition. The solution purging was for at least 4 hours before the test to achieve equilibrium for the system. The system equilibrium was confirmed by steady values of pH with time. The solution was continuously purged during the experiment to maintain the gas concentrations. The experimental results were compared with those obtained at 80 °C (simulating the rich-lean heat exchanger temperature condition).

**Electrochemical measurements**
The electrochemical corrosion measurements were carried out in a 0.5L glass cell at 50°C under atmospheric pressure. The setup included: a three-electrode corrosion cell (counter electrode, CE: platinum wire; reference electrode, RE: saturated calomel reference electrode (SCE) mounted on a salt bridge; working electrode, WE: carbon steel Q235); hot plate equipped with temperature controller (Bante instrument MS300); gas supply set (nitrogen, oxygen and carbon dioxide); potentiostat (Gamry Reference 1000 potentiostat/galvanostat/ZRA); pH meter (Sartorius PB-10, ±0.01) and conductivity meter (Shanghai precision and scientific instrument DDS-307A). All potentials in this work were measured versus SCE. Open circuit potential (OCP) measurements were conducted for 2 hours. The EIS measurement was conducted at OCP with a sinusoidal potential perturbation of 10 mV in a frequency range from 100 kHz to 10 mHz, and the obtained EIS spectra were fitted using the Gamry software. The potentiodynamic polarization tests were performed from -1.2 V to -0.7 V at 0.1667 mV/s sweep rate. The potentiodynamic polarization test and EIS measurement were performed when the OCP became relatively stable. Also, in order to quantify the different parameters involved in the EIS spectra, the plots were fitted with an electrical equivalent circuit which is presented in Fig. 1. Where Rₛ is the solution resistance, Rₐ and Cₐ relate to the charge transfer resistance and capacitance of the double layer, respectively, Rₜ and Cₜ relate to the film resistance and capacitance, respectively. In view of the distribution of relaxation times arising from the heterogeneous nature of the metal surface, a constant phase element (CPE) was employed to illustrate the frequency reliance of non-ideal capacitive behavior instead of the ideal capacitance hence improving the EIS spectra fitting quality [38, 39]. It should however be noted that for simplicity in expression, Cₐ and Cₜ were used.

**Weight loss measurements**
Assessments of the effects of the presence of sulfide with respect to sulfide concentration and solution temperature on the corrosion behavior of carbon steel in the test systems were carried out by weight loss measurements. The test systems were the same with those of the electrochemical measurements. This was to ensure close comparison between the two test methods. For evaluation of the effect of sulfide on the corrosion of carbon steel, the study was conducted for 0.05 M and 0.10 M sulfide concentration at 50 °C and immersion lasted for 7 days
and 14 days. For the evaluation of the effect of temperature, the test was conducted for 0.05 M sulfide at 50 °C and 80 °C, and immersion time of 7 days and 14 days. The coupons were pre-weighed and suspended in the test solutions. On expiration of the test duration (7 days and 14 days), the coupons were carefully retrieved, washed in a pickling acid solution, rinsed in distilled water, dipped in acetone, air dried and re-weighed. The weight loss was determined as the difference in weight of the carbon steel coupons before and after immersion in the test solution. Corrosion rate was calculated from the weight loss values using the expression [40]:

\[
\text{Corrosion rate (mm/y)} = \frac{8.76 \times 10^4 \times \text{weight loss (g)}}{\text{area (cm}^2\text{)} \times \text{density (g/cm}^3\text{)} \times \text{time (h)}}
\]  

(1)

**Fig. 1 The equivalent circuit used to fit the EIS spectra**

**Surface analysis**

The surface morphology and composition analysis of corrosion product film on the carbon steel coupons after immersion in the test system at different experimental conditions were detected by a scanning electron microscopy/energy dispersive X-ray detector (SEM/EDS, INSPECT F50). X-ray Diffraction (Panalytical X’Pert PRO, Cu Ka radiation at 40 kV, PA Analytical, Almelo, Holland) was used to analyze the phase component of the corrosion product film. Additionally, with the aim to further understand and characterize the nature of the corrosion product film, XPS analyses (A VG ESCALAB 250 X-ray photoelectron spectrometer with a monochromatic AlKα (1486.6 eV) radiation source) were performed on the corrosion product film.

**Results and discussion**

**Influence of sodium sulfide addition and sulfide concentration**

**Potentiodynamic polarization**

From Fig. 2 for the polarization curve of carbon steel in the system with and without sulfide, it is shown that the addition of sulfide majorly affected the anodic area as it induced a reduction in the anodic current, while the cathodic area remained more or less unchanged. This is an indication that the presence of sulfide reduced the corrosion rate of carbon steel. It is also shown that the potential of the system with sulfide increased. This further demonstrates the prospects of the inhibition of the anodic dissolution reaction of carbon steel impacted by the presence of sulfide. However, the plot also reveals that the protection offered by the 0.05 M sulfide was higher than that for 0.10 M sulfide. This observation implies that although sulfide caused a reduction in carbon steel corrosion, the efficiency of its inhibition is reduced when sulfide concentration is increased.
Fig. 2 Potentiodynamic polarization curves of carbon steel exposed to MDEA solution with and without sodium sulfide

EIS measurement
To verify the observation from the potentiodynamic measurements, EIS measurements conducted for carbon steel in the solution containing sulfide are presented in the Nyquist format (Fig. 3). Apparently, when 0.05 M sulfide was introduced to the system, the diameter of the spectrum increased. Increase in the concentration of sulfide (0.10 M) yielded a Nyquist plot with reduced diameter when compared with the former, signifying a decrease in the corrosion resistance of carbon steel with increasing concentration of sulfide.

Using the electrical equivalent circuit shown in Fig. 1, EIS data were fitted to obtain the required electrochemical parameters which are presented in Table 2. The table shows the values of polarization resistance ($R_p$) which is calculated as a sum of the charge transfer resistance ($R_{ct}$) and film resistance ($R_f$). The values confirm the concentration effect of sulfide on carbon steel corrosion.

Table 2 Electrochemical parameters obtained from the fitting of EIS spectra of carbon steel in the solution with sulfide

<table>
<thead>
<tr>
<th>MDEA Solution</th>
<th>$R_d$/Ω cm$^2$</th>
<th>$R_c$/kΩ cm$^2$</th>
<th>$C_{dl}$/μF cm$^{-2}$</th>
<th>n</th>
<th>$R_p$/kΩ cm$^2$</th>
<th>$C_f$/μF cm$^{-2}$</th>
<th>n</th>
<th>$R_p$/kΩ cm$^2$</th>
<th>Chi-square ($\times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without sulfide</td>
<td>52.8</td>
<td>2.21</td>
<td>15.7</td>
<td>0.92</td>
<td>60.2</td>
<td>307.7</td>
<td>0.89</td>
<td>62.41</td>
<td>2</td>
</tr>
<tr>
<td>0.05 M sulfide</td>
<td>55.1</td>
<td>9.53</td>
<td>61.6</td>
<td>0.91</td>
<td>240.5</td>
<td>246.4</td>
<td>0.94</td>
<td>250.03</td>
<td>2</td>
</tr>
<tr>
<td>0.10 M sulfide</td>
<td>47.7</td>
<td>7.31</td>
<td>40.2</td>
<td>0.85</td>
<td>127.3</td>
<td>251.3</td>
<td>0.91</td>
<td>134.61</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Time-dependent corrosion experiment
Time-dependent weight loss measurements were conducted to evaluate the effect of sulfide on the corrosion behavior of carbon steel in MDEA solution after 7 and 14 days exposure period. This is to establish information on the long term effects of the salt. The evaluation was done with respect to variations in both sulfide concentration and temperature.

Influence of sulfide concentration
From the knowledge that the lower sulfide concentration performed better as corrosion inhibitors for carbon steel in MDEA capture systems, 0.05M and 0.10 M sulfide were selected as the study concentration for the time-dependent corrosion experiments to represent low and high concentrations, respectively, while the immersion of carbon steel specimen in the MDEA solution containing sulfide lasted for 7 days and 14 days, respectively. This represented both short and long term exposure test durations. The tests were carried out under static flow conditions and the average corrosion rate of carbon steel calculated from equation (1) is presented in Fig. 4a. The average corrosion rate for the solution without sulfide after 7 days was 0.092 mm/year. This value increased to 0.102 mm/year after 14 days. The introduction of 0.05 M sulfide caused an appreciable reduction in the average corrosion rate of carbon steel after 7 days, yielding a value of 0.01 mm/year. This corresponds to 89.1 % inhibition efficiency. Furthermore, the corrosion rate was affected by immersion time as the value increased to 0.018 mm/year after 14 days exposure period. This led to a corresponding decrease in the inhibition efficiency to 82.4 %.

The presence of 0.10 M sulfide resulted to a different effect of the salt. It was observed that the average corrosion rate increased when sulfide concentration increased. After 7 days and 14 days immersion of the carbon steel specimen in the solution with 0.10 M sulfide, the recorded average corrosion rates were 0.023 mm/year and 0.032 mm/year, respectively. These values respectively correspond to an inhibition efficiency of 75.0 % and 68.6 %. Both the plots for the
time-dependent corrosion experiments of carbon steel in the MDEA solution with sulfide and their corresponding inhibition efficiencies are presented in Fig. 4.

![Graph of time-dependent corrosion experiment and inhibition efficiency](image)

Fig. 4 (a) Time-dependent corrosion experiment of carbon steel exposed to MDEA solution with and without sodium sulfide at 50 °C (b) Inhibition efficiency of the different sodium sulfide concentrations

Fig. 5 shows the SEM micrograph of the surface of carbon steel to further explain the action of 0.05 M sulfide after 7 days and 14 days immersion tests. The carbon steel surface after 7 days in the solution without sulfide, shows a complete surface coverage signifying a high corrosion rate for the early exposure period until a complete surface coverage by the corrosion product film (suggested to be majorly characterized by the presence of FeCO₃) which will decrease the corrosion rate with time. For the solution with 0.05 M sulfide, the test after 7 days shows the coverage of a finely placed film on the surface of the carbon steel specimen with the existence of visible polishing marks indicating some protectiveness against anodic metal dissolution. EDS analysis results (Table 3) showed that the corrosion product layer contained iron (Fe), carbon (C), oxygen (O) and sulfur (S). On longer exposure period (after 14 days), there was increased coverage of the carbon steel surface by corrosion products but the identified elements were unchanged.

<table>
<thead>
<tr>
<th>MDEA solution</th>
<th>C K</th>
<th>O K</th>
<th>S K</th>
<th>Fe K</th>
</tr>
</thead>
<tbody>
<tr>
<td>without sodium sulfide</td>
<td>14.15</td>
<td>37.96</td>
<td>-</td>
<td>47.88</td>
</tr>
<tr>
<td>with 0.05 M sodium sulfide</td>
<td>10.39</td>
<td>5.05</td>
<td>3.35</td>
<td>81.22</td>
</tr>
<tr>
<td>after 7 days</td>
<td>19.01</td>
<td>18.86</td>
<td>9.44</td>
<td>52.96</td>
</tr>
<tr>
<td>with 0.10 M sodium sulfide</td>
<td>9.02</td>
<td>7.22</td>
<td>6.70</td>
<td>77.06</td>
</tr>
<tr>
<td>after 7 days</td>
<td>20.77</td>
<td>17.38</td>
<td>10.04</td>
<td>51.81</td>
</tr>
</tbody>
</table>

When the concentration of sulfide was increased to 0.10 M, SEM micrograph after 7 day immersion showed that the carbon steel surface was more corroded as compared to that of 0.05 M sulfide and the polishing marks were less visible. After 14 days, the surface of the carbon steel coupon was completely covered by the corrosion product. This explains the high corrosion rate associated with the presence of high sulfide concentration described by the electrochemical and weight loss measurements. It therefore means that the high sulfide concentration contributed to
the formation of a loose corrosion product film which does not contribute to the inhibition actions of sulfide.

Fig. 5 SEM micrographs of carbon steel after immersion at 50 °C in MDEA solution containing (a) 0 M sodium sulfide after 7 days (b) 0.05 M sodium sulfide after 7 days (c) 0.05 M sodium sulfide after 14 days (d) 0.10 M sodium sulfide after 7 days and (e) 0.10 M sodium sulfide after 14 days

Influence of temperature
Time-dependent corrosion experiments on carbon steel were evaluated based on temperature variations. The tests were conducted at 50 °C and 80 °C for the experimental setup involving carbon steel specimen immersed in MDEA solution containing 0.05 M sulfide. Weight losses were measured after 7 days and 14 days and the results were applied in the corrosion rate expression as depicted by equation (1). Considering the variations in temperature for different sections of a typical CO₂ capture plant, the temperature-based time-dependent corrosion experiments were carried out to assess and estimate the extent of temperature effect on the corrosion behavior of carbon steel under short and long term exposures to MDEA solution.
containing 0.05 M sulfide. As presented by Fig. 4, the test for the solution without sulfide at 50 °C yielded carbon steel corrosion rates of 0.092 mm/year and 0.102 mm/year after 7 days and 14 days immersion, respectively. On the introduction of 0.05 M sulfide to the MDEA capture solution, the corrosion rates for the tests after 7 days and 14 days were 0.01 mm/year and 0.018 mm/year, respectively. These reductions in corrosion rates are in agreement with the observations and reports of the inhibition properties of low sulfide concentration. When the temperature was increased to 80 °C, the corrosion rate of carbon steel exposed to the MDEA solution containing 0.05 M sulfide increased to 0.047 mm/year and 0.055 mm/year, respectively, after 7 days and 14 days (Fig. 6a). The results show that at increased temperature, the rate of dissociation of molecules increased, thereby leading to an increase in the number of sulfide ions in the system. This equates with the reports of electrochemical measurements which shows that with increase in the concentration of sulfide (increase in the number of ions), the corrosion rate of carbon steel increased. Therefore, it is safe to conclude that the increase in temperature led to an increase in the number of sulfide ions which resultedly led to a reduction in sulfide inhibition of carbon steel corrosion.

The plot of inhibition efficiency of sulfide with respect to temperature for the time-dependent corrosion experiment is presented in Fig. 6b. With increase in temperature, the inhibition efficiency decreased from 89.1 % for the test at 50 °C to 48.9 % for the test at 80 °C after 7 days immersion. After 14 days immersion, the inhibition efficiency decreased from 82.4 % to 46.1% for 50 °C and 80 °C, respectively.

![Fig. 6 (a) Temperature-dependent corrosion rate of carbon steel exposed to MDEA solution containing 0.05 M sodium sulfide after different days (b) Temperature-dependent inhibition efficiency of 0.05 M sodium sulfide after different days](image)

On evaluation of the influence of temperature on corrosion rate, SEM analyses on carbon steel surface were carried out after 7 days and 14 days immersion in the solution containing 0.05 M sulfide at 80 °C and the results were compared with those of carbon steel carried out at 50 °C. Fig. 7 shows that the corrosion rate after 7 days were higher than that reported for the same duration at 50 °C with the presence of larger crystal grains which grew on the fine film reported for the former. This illustrates the corrosion promoting effect of temperature even in the presence of a corrosion inhibitor. After 14 days, there was a total surface coverage by corrosion product film.
Corrosion mechanism of carbon steel in the presence of sulfide

The electrochemical and weight loss measurements were consistent with the observation of inhibition effects of sulfide on carbon steel surface and SEM/EDS analyses revealed the presence of a sulfur-based corrosion product layer in addition to the primary FeCO$_3$ layer. These were generally in agreement with findings by Choi et al. [41] where the introduction of H$_2$S activated a deceleration in the CO$_2$ corrosion rate of carbon steel found in acidic solutions. The deceleration was reported to be as a result of the formation of a thin iron sulfide (FeS) film. Equation (2) describes that the film is formed by reaction between Fe$^{2+}$ and the sulfide ion:

$$\text{Fe}^{2+} + \text{S}^{2-} \rightarrow \text{FeS}$$

Fig. 7 SEM micrographs of carbon steel after immersion at 80 °C in MDEA solution containing (a) 0 M sodium sulfide after 7 days (b) 0.05 M sodium sulfide after 7 days and (c) 0.05 M sodium sulfide after 14 days

The FeS film was further reported to display two characteristic and completely different properties on the corrosion behavior of carbon steel; at low sulfide concentrations, the film impedes the corrosion process proportional to the film surface coverage but shows little effect on the movement of electrons through the film to encourage cathodic reactions. At high sulfide concentrations, the film caused an increase in the corrosion process, by possibly encouraging cathodic reactions with increased surface area [42]. Furthermore, extra inhibition effects may have been imparted by the reducing property and oxygen scavenging ability of sodium sulfide. However, these may be the secondary effects as sulfide is usually consumed quickly in the presence of oxygen [43].

To confirm the presence of the FeS scale, surface analyses of carbon steel by XRD and XPS were carried out. Fig. 8 which corresponds to the results of XRD analysis shows that the carbon steel surface contained FeCO$_3$ as the primary corrosion product while the presence of Fe characterized the other peaks. This method could not account for the presence of the sulfur-based compound observed by the SEM/EDS analysis.

Fig. 9 presents the XPS results of carbon steel after immersion for 7 days in the MDEA solution containing 0.05 M sulfide. An examination of the scan of the corrosion film confirms the presence of FeCO$_3$, Fe$_2$O$_3$ and FeS by identifying the following elements and their corresponding binding energies: FeCO$_3$ (Fe 2p$_{3/2}$ ≈710.2 eV, O 1s ≈531.9 eV and C 1s ≈289.2 eV), Fe$_2$O$_3$ (Fe 2p$_{3/2}$≈711.4 eV, O 1s ≈530.1 eV) and FeS (Fe 2p$_{3/2}$≈712.7 eV). The confirmation of the formation of FeS validates equation (2) while Fe$_2$O$_3$ is accounted for by equations (3) and (4) where FeCO$_3$ decomposes at temperatures below 100 °C to produce ferrous oxide (FeO) which transforms quickly in the presence of oxygen to Fe$_2$O$_3$ as shown [44]:
FeCO$_3$ → FeO + CO$_2$  \hspace{1cm} (3)
4FeO + O$_2$ → 2Fe$_2$O$_3$  \hspace{1cm} (4)

Fig. 8 XRD pattern of the corrosion product film formed on the surface of carbon steel immersed for 7 days at 50 °C in MDEA solution (a) without (b) with sodium sulfide

Fig. 9 XPS spectra of the corrosion product film formed on the surface of carbon steel immersed for 7 days at 50 °C in MDEA solution (a) without (b) with sodium sulfide
Summary

The study focused on the corrosion behavior of carbon steel in a CO$_2$-saturated MDEA solution containing sodium sulfide (Na$_2$S) under static flow conditions. The influence of sulfide concentration was investigated with respect to immersion time and temperature variation. The conclusions are as follows: Sodium sulfide exhibited two characteristic and completely different effects on the corrosion behavior of carbon steel. These effects depended largely on the concentration of the salt. Sulfide performed as an excellent corrosion inhibitor for carbon steel corrosion at a low concentration. The inhibition property diminished with increase in sulfide concentration. The presence of low sulfide concentration forms a thin corrosion film which inhibits the corrosion process proportional to the carbon steel surface coverage. This film does not permit the movement of electrons needed to activate cathodic processes. On the other hand, the high sulfide concentration forms a film with increased surface area on the carbon steel surface which encourages the movement of electrons on the surface and allowing cathodic processes to occur, hence, increasing the corrosion rate. Surface analysis revealed the formation of FeCO$_3$ as the primary corrosion product on the surface of carbon steel while Fe$_2$O$_3$ was reported as an additional product layer formed from the decomposition of FeCO$_3$ (usually at temperatures below 100 °C). The presence of FeS scale was identified as the corrosion product introduced by the reaction of sodium sulfide and Fe$^{2+}$. Influence of sulfide concentration on the time-dependent corrosion experiment shows that for the 0.05 M sulfide, the inhibition efficiency decreased from 89.1 % after 7 days to 82.4 % after 14 days while it decreased from 75.0 % to 68.6 % corresponding to 7 days and 14 days, respectively, for the system with 0.10 M sulfide. Temperature generally increased the corrosion rate of carbon steel in the system containing sulfide. For 0.05 M sulfide, the corrosion rate increased from 0.01 mm/year at 50 °C to 0.047 mm/year at 80 °C after 7 days and 0.018 mm/year to 0.055 mm/year after 14 days.

Acknowledgement

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