Advantages of asymmetrical over symmetrical cells for detection of under deposit CO₂ corrosion using electrochemical noise

Mahdieh Zeidabadinejad | Mehdi Shahidi-Zandi | Mohammad Mehdi Foroughi | Hamideh Asadollahzadeh

Electrochemical noise (EN) measurements were done on symmetrical and asymmetrical cells after immersion in 3.5% NaCl solutions saturated with CO₂ and containing different concentrations of sodium bicarbonate to get a better interpretation of the under-deposit corrosion of mild steel. The symmetrical cell was constructed from two sand-deposited electrodes and the asymmetrical cell was prepared from one sand-deposited electrode and one bare electrode. The combination of the standard deviation of partial signal (SDPS) plots arising from wavelet analysis and recurrence plots for analyzing the EN signals obtained from symmetrical and asymmetrical cells confirmed the higher detective ability of the asymmetrical cells in comparison with the symmetrical cells for measuring the under-deposit corrosion of mild steel. Both the SDPS and recurrence plots arising from symmetrical cells showed no significant change in the corrosion severity of the steel alloy with adding sodium bicarbonate. In contrast, the SDPS and recurrence plots of the asymmetrical cells proved that the corrosion severity decreased initially with adding the bicarbonate and thereafter remained constant with increasing the bicarbonate concentration. The optical microscopy images of the sand-covered electrode surface confirmed the latter result.

KEYWORDS
asymmetrical cells, electrochemical noise, recurrence plots, under-deposit corrosion (UDC), wavelet analysis

1 | INTRODUCTION

The settling of deposits such as sand in the pipelines of the oil and gas industries exacerbates the corrosion of steel pipelines. This event which is called under-deposit corrosion (UDC) is accompanied with pitting corrosion.[1] The UDC is worth considering because it can lead to pipeline leaking.[2] The sands lead to depositing the corrosion product locally on the steel surface by blocking the transport of the corrosion product into the solution bulk. Therefore, the severity of UDC increases first and then decreases with time.[2]

CO₂ corrosion is an important problem in oil and natural gas exploration, production and transportation due to the presence of CO₂ in oil wells.[3–5] For example, the internal corrosion of pipelines can be considered to be caused by the dissolved CO₂ in the aqueous phase.

Several papers have been published on the effect of CO₂ on the corrosion of steel alloys.[3–14] CO₂ corrosion of
CO₂ increases the corrosion rate of steel alloys by promoting both cathodic and anodic reactions. The main cathodic reactions in aqueous CO₂ environments are the reduction reactions of H⁺, H₂CO₃, HCO₃⁻, and water:[15]

\[ 2H_2O_{(aq)} + 2e^- \rightarrow H_2(g) + 2OH^-_{(aq)} \]  \hspace{1cm} (4)
\[ 2HCO_3^-(aq) + 2e^- \rightarrow H_2(g) + 2CO_2(aq) \]  \hspace{1cm} (3)
\[ 2H_2CO_3(aq) + 2e^- \rightarrow H_2(g) + 2HCO_3^-(aq) \]  \hspace{1cm} (2)
\[ 2H^+_2CO_3(aq) + 2e^- \rightarrow H_2(g) + 2HCO_3^-(aq) \]  \hspace{1cm} (1)

The proton ions arising from dissociation of H₂CO₃ can be reduced according to Equation (1). In addition, the direct reduction of H₂CO₃ (Equation (2)), HCO₃⁻ (Equation (3)) and water (Equation (4)) may occur at the alloy surface. However, there is some debate concerning the exact cathodic reaction taking place at the surface. It is generally agreed that the hydrogen reduction reaction (Equation (1)) is the dominant cathodic reaction at pH range 3–5.5 and the other reactions (Equations (2–4)) can be considered to be significant at more basic pH values.[16]

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The main anodic reaction is the Fe oxidation reaction. Recently, a mechanism has been proposed for the Fe anodic dissolution involving the formation of an adsorbed intermediate with HCO₃⁻(aq) as the rate determining step (RDS)[17]:

\[ \text{Fe}(s) + \text{HCO}_3^-(aq) \rightarrow \text{FeHCO}_3^+(ad) + e^- \]  \hspace{1cm} (5)
\[
\text{FeHCO}_3^+(ad) \leftrightarrow \text{FeHCO}_3^+(ad) + e^- \]
\[
\text{FeHCO}_3^+(ad) \leftrightarrow \text{Fe}^{2+}(aq) + \text{HCO}_3^-(aq) \]

The current fluctuations arising from localized corrosion events, called electrochemical noise (EN) signals, have been used broadly for the investigation of general and localized corrosion processes.[18–25] For recording the EN signals, two identical working electrodes (WEs) are connected by a zero-resistance ammeter (ZRA).

Wavelet transform (WT), as a mathematical approach, is a popular tool for analyzing EN signals.[26–32] It is possible to obtain the standard deviation of partial signal (SDPS) from the WT.[32] SDPS is a criterion of the corrosion activity of the electrodes’ surface within a particular time interval.

The maximum peak in the SDPS plot represents the predominant transients for each signal.

The recurrence plots (RPs) technique is a graphical way to visualize the recurrence features of many nonlinear dynamic systems.[33] The formal concept of recurrence states that an initial state or configuration of a mechanical system, subjected to conservative forces, will reoccur again in the course of the time evolution of the system.[34] RPs accompanied by recurrence quantification analysis (RQA) is an advanced tool suitable for the analysis of dynamic systems.[35,36]

An N × N recurrence matrix can be denoted by the following equation:

\[ R_{ij}(\varepsilon) = H(\varepsilon - ||x_i - x_j||), \quad i, j = 1, 2, ..., N \]  \hspace{1cm} (8)

where N is the number of states in phase space, ε is a predefined threshold radius, xᵢ, xⱼ are the points in phase space occurring at times i and j, ||·|| denotes the Euclidean norm of the vectors, and H represents the Heaviside function. If the distance between xᵢ and xⱼ falls within the threshold radius, then Rᵢⱼ = 0, otherwise, Rᵢⱼ = 1. The RPs is the two-dimensional graphical representation of Rᵢⱼ. In the RP a “white” dot is assigned to the value zero (Rᵢⱼ = 0) and a “black” dot to the value one (Rᵢⱼ = 1).

The methodology of RP does not require stationarity or linearity of data. This advantage is supplemented by the independence of the RP on the constraints, such as the data set size. Therefore, RP is very useful for analyzing the electrochemical noise data.[35,37–42]

RQA is a developed approach based on the RP for the quantitative analysis of dynamic systems. There are three types of RQA parameters extracting point-wise, diagonal-wise and laminar-wise statistics, defined as recurrence rate (R), determinism (D) and laminarity (Lₘᵦₚ), respectively.[42] The recurrence rate, R, is the percentage of the recurrence plot occupied by recurrent points:[34]:

\[ R = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{ij}(\varepsilon). \]  \hspace{1cm} (9)

Determinism D is the percentage of the recurrent points forming line segments parallel to the main diagonal:

\[ D = \frac{\sum_{l=1}^{l_{\text{max}}} lP(l)}{\sum_{i,j=1}^{N} R_{ij}(\varepsilon)}. \]  \hspace{1cm} (10)

where P(l) is the number of diagonal lines with length l in RP, and lₘᵦₚ is the smallest size for a row to be considered a diagonal (usually lₘᵦₚ = 2).
Laminarity $L_{am}$ is the analog of $D$ for vertical (or horizontal) lines, and it is the ratio between the recurrence points forming the vertical structures and the entire set of recurrence points:\[33\]:
\[
L_{am} = \frac{\sum_{v=v_{\text{min}}}^{N} vP(v)}{\sum_{v=1}^{N} vP(v)}.
\]

where $P(v)$ is the number of vertical lines with length $v$ in RP, and $v_{\text{min}}$ is the smallest size for a row to be considered a vertical line. Vertical (or horizontal) lines on an RP denote that the system state does not change or changes very slowly in time.

Trapping time TT estimates the average time interval in which the system will be trapped in a given state, without varying it considerably:
\[
TT = \frac{\sum_{v=v_{\text{min}}}^{N} vP(v)}{\sum_{v=1}^{N} P(v)}.
\]

The TT parameter contains information about the amount and the length of the vertical structures in the RP.\[33\]

In this paper, the UDC of mild steel in 3.5% NaCl solutions saturated with CO$_2$ was investigated under different concentrations of bicarbonate. The present work attempts to investigate the combination of the SDPS plots and RP for analyzing the EN signals obtained from symmetrical and asymmetrical cells to get a better interpretation of the UDC of mild steel.

<table>
<thead>
<tr>
<th>Run</th>
<th>Solution</th>
<th>WE condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS0</td>
<td>CO$_2$ sat + 3.5% NaCl</td>
<td>sand-covered (WE1-WE2)</td>
</tr>
<tr>
<td>SS2</td>
<td>CO$_2$ sat + 3.5% NaCl + 0.02% NaHCO$_3$</td>
<td>sand-covered (WE1-WE2)</td>
</tr>
<tr>
<td>SS5</td>
<td>CO$_2$ sat + 3.5% NaCl + 0.5% NaHCO$_3$</td>
<td>sand-covered (WE1-WE2)</td>
</tr>
<tr>
<td>SB0</td>
<td>CO$_2$ sat + 3.5% NaCl</td>
<td>sand-covered (WE1) + bare (WE2)</td>
</tr>
<tr>
<td>SB2</td>
<td>CO$_2$ sat + 3.5% NaCl + 0.02% NaHCO$_3$</td>
<td>sand-covered (WE1) + bare (WE2)</td>
</tr>
<tr>
<td>SB5</td>
<td>CO$_2$ sat + 3.5% NaCl + 0.5% NaHCO$_3$</td>
<td>sand-covered (WE1) + bare (WE2)</td>
</tr>
</tbody>
</table>

Abbreviation: WE, working electrode.

2 | EXPERIMENTAL

Two nominally identical mild steel samples with the surface area of 100 mm$^2$ were used as working electrodes (WE1 and WE2). Two test cells, called symmetrical and asymmetrical cells, were set up for the electrochemical noise measurement. The symmetrical cell was constructed from two sand-deposited electrodes (WE1 and WE2) and the asymmetrical cell was prepared from one sand-deposited sample and one bare sample. The experimental conditions are listed in Table 1.

Silica sand (SiO$_2$) was acid-washed and dried before use. To prepare the sand-deposited (or sand-covered) electrode, the WE was placed at the bottom of the glass cell and the test solution containing silica sand was poured on it to be covered by a layer of silica sand. In all experiments, 10 g of sand was used ensuring a consistent layer of about 5 mm of the sand deposit on the steel surface. The test solutions were 3.5% NaCl solutions saturated with CO$_2$ and containing different concentrations of sodium bicarbonate (0.02% and 0.5%). All measurements were performed under stagnant conditions and ambient CO$_2$ pressure.

After connecting the disk shape specimens to a copper wire and sealing them using resin, the prepared WEs were polished by wet abrasive papers through 600–2,500 grade. Then, they were washed with distilled water and ethanol. The electrodes were immersed in the solution by facing each other vertically. The reference electrode was a saturated (KCl) Ag/AgCl electrode.

An Autolab 302 N potentiostat (from Metrohm Autolab Company) equipped with Nova 1.9 software was used to conduct the electrochemical noise tests. The EN signals were recorded over 5 min after 30 min soaking. The optical microscopy images of the working electrode surface were recorded by using a digital microscope (Company of Sino Age Development Technology) (JM300).

The EN data were gathered with the sampling frequency of 16 Hz. The wavelets of orthogonal Daubechies with the fourth order (db4) were used for analyzing the EN data by the wavelet technique. The Matlab software was used for constructing the SDPS and RP.

A Matlab toolbox developed by Marwan et al.\[33\] was used for constructing the RP of EN data (provided by TOCSY: http://tocsy.pik-potsdam.de/CRPtoolbox).

The RP were calculated after wavelet trend removal of EN signals. The wavelet trend removal can eliminate the
drift component of the EN signals while conserving the useful information of the EN data.

3 | RESULTS AND DISCUSSION

3.1 | Symmetrical cells

EN measurements were performed on symmetrical cells made of mild steel samples in a 3.5% NaCl solution saturated with CO₂ having NaHCO₃ concentrations of 0%, 0.02%, and 0.5%. The recorded EN signals are shown in Figure 1.

The SDPS signals (as shown in Figure 2) were constructed from the WT of the EN signals. The crystal corresponding to the maximum SDPS value in the SDPS plot presents the predominant transients of each signal. The SDPS plot of Signal SS0 peaks at the crystals of d3, d5, and d7 (Figure 2). Table 2 shows the timescale ranges of the d1 to d8 crystals in the case of $f_s = 16$ Hz. According to Figure 3, a closer inspection of the EN signal revealed that the latter crystals (i.e., d5 and d7) corresponded to the overlapped transients while the former crystal (i.e., d3) corresponded to the single transients. Therefore, the true timescale of the predominant transients of Signal SS0 corresponds to the d3 crystal rather than to the d5 or d7 crystal.

Table 3 outlines the timescales and the SDPS values of the predominant transients of EN signals arising from the symmetrical cells. It is apparent from Figures 3 and 4 that all signals arising from symmetrical cells showed d3 crystal as the true timescale of the predominant transients. Since the predominant transients can be attributed to metastable pits, it can be deduced that the size of the generated pits on the alloy surface should not change with adding sodium bicarbonate. This result is in contrast with that of the optical microscopy images in Figure 5, which shows a decrease in the pit size with adding sodium bicarbonate.

An interesting feature of the SDPS plots is the ability to quantify the corrosion severity. The predominant current transients result from the metastable pits occurring on the mild steel surface. The quantity of electric charge which is produced from pitting corrosion on the alloy surface can be estimated by the following equation:

$$Q = i_{\text{max}} \cdot \tau_{\text{max}} \cdot (13)$$

where $i_{\text{max}}$ is the SDPS value at the maximum peak crystal ($d_{\text{max}}$) and $\tau_{\text{max}}$ is the average time width of the $d_{\text{max}}$ crystal. For example, the maximum of the SDPS plot of Signal SS0 in Figure 2 is located at the d3 crystal with

![Image 1](image1.png)

FIGURE 1  Electrochemical noise signals of symmetrical sand-deposited electrodes made of mild steel after 30 min soaking in 3.5% NaCl solutions saturated with CO₂ and containing (a) 0%, (b) 0.02%, and (c) 0.5% bicarbonate.

![Image 2](image2.png)

FIGURE 2  Standard deviation of partial signal plots of electrochemical noise signals in Figure 1.

![Image 3](image3.png)

TABLE 2  Timescale ranges for $f_s = 16$Hz

<table>
<thead>
<tr>
<th>Crystal name</th>
<th>Timescale range (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d1</td>
<td>0.0625–0.125</td>
</tr>
<tr>
<td>d2</td>
<td>0.125–0.25</td>
</tr>
<tr>
<td>d3</td>
<td>0.25–0.5</td>
</tr>
<tr>
<td>d4</td>
<td>0.5–1</td>
</tr>
<tr>
<td>d5</td>
<td>1–2</td>
</tr>
<tr>
<td>d6</td>
<td>2–4</td>
</tr>
<tr>
<td>d7</td>
<td>4–8</td>
</tr>
<tr>
<td>d8</td>
<td>8–16</td>
</tr>
</tbody>
</table>
the SDPS value of 22.8 nA \( (i_{\text{max}}) \). Referring to the sampling frequency of 16 Hz, the average time width of the crystal d3 \( (\tau_{\text{max}}) \) is equal to 0.375 s (Table 2), and thereby the Q value will be 8.6 nC. The Q value is a measure of the corrosion severity of the alloy surface.

The Q values derived from all the SDPS plots in Figure 2 have been listed in Table 3. The Q values in Table 3 do not appear to change significantly with adding the sodium bicarbonate to the electrolyte solution, and therefore, the corrosion severity of the steel alloy should not change significantly by adding bicarbonate. This is not in agreement with both Figure 5 and the previous result suggesting that the corrosion rate of mild steel in CO₂-saturated NaCl solutions decreased by adding NaHCO₃.[15]

The RP of the EN signals are shown in Figure 6. Each of the signals contained 4,800 data points, equivalent to a time frame of 300 s. After removing the trend of each EN signal through wavelet analysis,[44] the RP were generated by applying a threshold \( (\varepsilon) \) to the distance matrices derived from each signal. The threshold value has a significant influence on the appearance of the RP. In general, the threshold \( \varepsilon \) has to be chosen to be as small as possible, but a too small \( \varepsilon \) can lead to false recurrences, which is expressed in numerous vertical structures.[40] On the other hand, if \( \varepsilon \) is too large, almost all points will

**Table 3** The maximum time scales, the corresponding SDPS and Q values of the predominant transients of EN signals arising from symmetrical cells soaking in 3.5% NaCl solution saturated with CO₂ and containing different bicarbonate concentrations

<table>
<thead>
<tr>
<th>Signal</th>
<th>( d_{\text{max}} )</th>
<th>SDPS (nA)</th>
<th>Q (nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS0</td>
<td>d3</td>
<td>22.8</td>
<td>8.6</td>
</tr>
<tr>
<td>SS2</td>
<td>d3</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>SS5</td>
<td>d3</td>
<td>0.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Abbreviations: EN, electrochemical noise; SDPS, Standard deviation of partial signal plot.
be identified as the recurrence points. In the present work, the threshold value was selected based on the standard deviation of the detrended EN time records.

The RPs in Figure 6 have a homogenous pattern with some vertical segments but little diagonal structure. The vertical black lines in the RP are caused by the current transients of the EN signal. Therefore, a higher density of the vertical black lines indicates a higher generation frequency of transients and thereby a higher pit density on the electrode surface.
It can be seen from Figure 6 that the number of vertical lines in the RPs remains almost unchanged by adding bicarbonate to the CO₂ saturated solution. This is an indication of the unchanged pit density with adding the bicarbonate. This result is consistent with the above result of the SDPS plots arising from wavelet analysis.

Some parameters, which quantify the small scale structures in RPs, known as RQA, help to go beyond the visual notion yielded by RPs. Table 4 lists the RQA parameters for EN signals shown in Figure 1.

R% is the ratio of the number of recurrent states (white dots) to all possible states (both white and black dots). This means that a lower R% value revealed a higher generation frequency of EN transients. Therefore, the same R% value of signals indicated the same population of transients and thereby identical pit density on the alloy surface with adding bicarbonate to the solution.

As mentioned above, the average length of vertical structures is given by the TT parameter. The TT value will increase if the RP consists of more white vertical structures (or less black vertical structures). The black vertical structure is the measure of the number of transients in the EN signal and represents the occurrence

<table>
<thead>
<tr>
<th>Signal</th>
<th>SD (nA)</th>
<th>ε (nA)</th>
<th>R%</th>
<th>D%</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS0</td>
<td>64</td>
<td>64</td>
<td>12.2</td>
<td>39.3</td>
<td>2.5</td>
</tr>
<tr>
<td>SS2</td>
<td>1.8</td>
<td>2</td>
<td>12.3</td>
<td>23.9</td>
<td>2.3</td>
</tr>
<tr>
<td>SS5</td>
<td>2.1</td>
<td>2</td>
<td>12.1</td>
<td>23.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Abbreviations: EN, electrochemical noise; RQA, recurrence quantification analysis; SDPS, Standard deviation of partial signal plot; TT, trapping time.

*Standard deviation of detrended signals.
of pitting corrosion on the surface of the alloy. It can be seen from Table 4 that the Signal SS0 contains the same TT values in comparison with two other signals. This means that the TT value remained unchanged with adding the bicarbonate to the solution. This is an indication of the unchanged pit density with increasing the bicarbonate to the solution. This is in agreement with the above result of the SDPS plots. Unfortunately, this result is not in agreement with that of the optical microscopy images in Figure 5.

### 3.2 Asymmetrical cells

EN tests were done on asymmetrical cells of mild steel in 3.5% NaCl solution containing different concentrations of bicarbonate. The obtained EN signals are shown in Figure 7. Figure 7 deriving from the asymmetrical cells shows unidirectional EN signals while Figure 1 resulting from the symmetrical cells presents bidirectional EN records. The unidirectional signals arise from the higher allocation of the anodic and cathodic reactions to different WEs.[25] The anodic reaction takes place mainly on the sand-covered WE and the cathodic reaction on the bare WE. But, the bidirectional EN signals result from the corrosion pits taking place on both of the two WEs.

The corresponding SDPS plots of the EN signals arising from asymmetrical cells are given in Figure 8. Table 5 outlines the maximum timescales and the corresponding SDPS values of the predominant transients of EN signals.

The maximum peak of the SDPS plots arising from Signals SB0, SB2, and SB5 locates at the crystals of d6, d1, and d1, respectively. This proves that the time width of the predominant transients of Signal SB0 is longer than that of Signals SB2 and SB5. However, with adding the bicarbonate, both the time width and the SDPS values decreased (Table 5), as evidence of less intense corrosion processes. On the other hand, the decrease of the time width (from d6 to d1) with adding the bicarbonate can be attributed to the decrease of corrosion activity, which was caused mainly by the decrease in the pit size on the surface of the steel alloy.

According to the Q values listed in Table 5, the corrosion severity of the alloy decreased with adding the bicarbonate. It is interesting to compare the Q values obtained after immersion in CO₂ saturated NaCl solution in the absence and the presence of sodium bicarbonate (Table 5). The Q values were lower significantly in the presence of bicarbonate than in the absence condition and then remained nearly constant as the bicarbonate...
concentration increased. This is in agreement with the previous result suggesting that the corrosion rate of mild steel in CO$_2$-saturated NaCl solutions first decreased and then remained nearly constant with increasing NaHCO$_3$ concentration.$^{[15]}$

After the wavelet trend removal, the resulting EN signals were analyzed to construct the RP as shown in Figure 9. The RPs in Figure 9 show that the number of vertical lines increased initially with adding the bicarbonate and thereafter remained constant with increasing the bicarbonate concentration up to 0.5%.

This behavior was confirmed by the RQA parameters given in Table 6. One can observe a nearly constant value of D% at about 86% to 97%, which corresponds physically to pitting corrosion.$^{[45]}$ The lower values of R% and TT parameters of Signals SB2 and SB5 in comparison with Signal SB0 confirmed the increasing generation frequency of the EN transients with adding the bicarbonate.

For Signals SB2 and SB5, the values of R% (and also TT) were nearly identical to each other. This means that the generation frequency of the EN transients remained constant with increasing the bicarbonate concentration from 0.02% to 0.5%.

The measurements on asymmetrical cells were carried out using the same conditions as used for the symmetrical cell measurements except the position of WEs. Therefore, the difference between the results of asymmetrical and symmetrical cells is due to the superior EN detection of the asymmetrical cell compared to the symmetrical cell. It can be seen from Figure 5 that the CO$_2$ corrosion of steel alloy shows a higher corrosion severity in the absence of bicarbonate than in the presence condition. It seems that the SDPS and RP of the asymmetrical cells, rather than those of the symmetrical cells, are in more agreement with both the optical microscopy images of sand-covered WE (Figure 5) and the previous result suggesting that the corrosion severity of mild steel in CO$_2$-saturated solutions first decreased and then remained nearly constant as the bicarbonate increased.$^{[15]}$

### Table 5

<table>
<thead>
<tr>
<th>Signal</th>
<th>$d_{max}$</th>
<th>SDPS (nA)</th>
<th>Q (nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB0</td>
<td>d6</td>
<td>197</td>
<td>591</td>
</tr>
<tr>
<td>SB2</td>
<td>d1</td>
<td>2.1</td>
<td>0.2</td>
</tr>
<tr>
<td>SB5</td>
<td>d1</td>
<td>6.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Abbreviations: EN, electrochemical noise; SDPS, Standard deviation of partial signal plot.

### Table 6

<table>
<thead>
<tr>
<th>Signal</th>
<th>SD$^2$/nA</th>
<th>$\varepsilon$/nA</th>
<th>R%</th>
<th>D%</th>
<th>TT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB0</td>
<td>418</td>
<td>418</td>
<td>25</td>
<td>97</td>
<td>25</td>
</tr>
<tr>
<td>SB2</td>
<td>36</td>
<td>36</td>
<td>11.2</td>
<td>86</td>
<td>5.9</td>
</tr>
<tr>
<td>SB5</td>
<td>140</td>
<td>140</td>
<td>10.9</td>
<td>91</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Abbreviation: EN, electrochemical noise; RQA, recurrence quantification analysis; TT, trapping time.

$^a$Standard deviation of detrended signals.

### CONCLUSIONS

Two configurations of symmetrical and asymmetrical cells were used for measuring the electrochemical noise (EN) to get a better interpretation of the UDC of mild steel. The sand-covered WE electrode was prepared by placing the WE at the bottom of the glass
cell and pouring the test solution containing silica sand on it. The EN tests were done after immersion of WEs in 3.5% NaCl solutions saturated with CO2 and containing different concentrations of sodium bicarbonate (0.02% and 0.5%). The combination of the SDPS and RP confirmed that the asymmetrical cells prepared from one sand-deposited electrode and one bare electrode contain a higher detective ability for measuring the UDC of mild steel in comparison with the symmetrical cells which were made of two sand-deposited electrodes.

In accordance with the optical microscopy images of the sand-covered electrode, the analysis of the asymmetrical cells confirmed that the corrosion severity decreased initially with adding the bicarbonate and thereafter remained constant with increasing the bicarbonate concentration.

**REFERENCES**
