Adsorption and corrosion inhibition behavior of polyethylene glycol on α-brass alloy in nitric acid solution

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ABSTRACT
The corrosion performance of α-brass in 1 M HNO 3 and in the presence of polyethylene glycol (PEG) has been investigated using AC impedance spectra (EIS), potentiodynamic polarization (PP), electrochemical frequency modulation (EFM), and mass reduction (MR) techniques. The outcome data of EIS showed a rise in the resistance charge transfer (R ct) and a decrease in the capacitance double layer (C dl). Protection efficiency (IE) of PEG has been obtained by varying the dose of the PEG and temperature. PEG adsorbed on α-brass in acidic solution follows isotherm Langmuir. The polarization curves displayed that PEG acts as a mixed-kind inhibitor. The parameters obtained from thermodynamic activation of corrosion α-brass in 1 M HNO 3 were obtained and debated. The results obtained from all tests were in excellent agreement.

1. Introduction
α-Brass has good thermal and electrical conductivity, best resistance for corrosion and wide uses. It is broadly utilized in the cooling systems, distillation plants, valves, and condensers systems. α-Brass is typically utilized in structure rails, fronts, door knobs, lock bodies, etc. Destructive acid medium has been generally used as a part of the manufacturing. The most important steps are acid pickling, manufacturing acid cleaning, decaling and oil acidizing well (1, 2). Dissolution prevention is considered so as to lessen the rates of corrosion on α-brass in this acidic medium (3–8). An inhibitor is a material utilized to lower the rate of corrosion by the absorption on the metal surfaces (9, 10). Many organic compounds are used as excellent inhibitors for α-brass because they contain donation π-electron, while others might give this donation by the organic compounds existing in the extracts (11–15). The use of natural products and organic compounds otherwise identified as “green corrosion inhibitors” has been supported because of the cost, toxic nature and environmentally unfriendliness of inorganic and organic corrosion inhibitors. More so, they are readily available, cheap, and a renewable source of materials. The use of polymers as corrosion inhibitors has attracted considerable attention recently. The polymers utilized as corrosion inhibitors have been highly considered newly due to the following factors: (1) they are low cost and are stable to metallic materials in aqueous solutions, (2) proprietorship of multiple sites’ adsorption, and (3) some studies concluded that their functional groups can form complexes with metal ions’ surface and protect the surface of metals (16–20). Some polymers are declared as corrosion inhibitors in dissimilar destructive media (21–24). Some of these polymers are polyethylene glycols (PEGs, 25–32). The protective power of these polymers is connected structurally to the cyclic rings, heteroatom. Several polymers have been described to prevent the corrosion of α-brass in numerous aqueous solutions (33–36). However, no examinations have described about the protective influence of PEGs on α-brass corrosion. In the current work, authors examine the corrosion hindrance activity of PEG by utilizing electrochemical and non-electrochemical tests that described to be a very active corrosion inhibitor for the mild steel protection (37) in aqueous solution to encourage an eco-friendly environment.

In the present study, it is intended to examine the influence of PEG dose and temperature on the corrosion behavior of α-brass alloy in 1 M HNO 3, and to compare corrosion protection data derived from EFM with that obtained from AC impedance spectra (EIS), potentiodynamic polarization (PP) and mass reduction (MR) tests. The surface morphology of α-brass utilizing: scanning electron microscopy (SEM), Fourier transform infrared
spectra (FT-IR), and atomic force micrographs (AFM) and the influence of the temperature on corrosion rate to calculate the thermodynamic parameters of activation and adsorption processes.

2. Experimental details

2.1. Composition of α-brass samples in weight % is: Fe 0.002, Pb 0.029, Zn 32.68, and Cu rest

2.2. Chemicals and solutions

The aggressive solution 1 M HNO₃ was prepared by dissolving the analytical reagent HNO₃ (70%) with second distilled water, and its dose was tested by standardized NaOH solution. The doses utilized (50–300 ppm) were obtained by dilution with second distilled water. The structure of the PEG is shown below with the molecular formula C₂₃H₄₇O₄₅+1

2.3. Methods utilized for corrosion tests

2.3.1. MR method

The MR investigations were accepted by utilizing square specimens of area 2 × 2 × 0.2 cm. The coins were first abraded to a mirror finish (600, 800, and 1200), degreased in acetone, and lastly cleansed with second distilled water and dried before being weighed and after that inundation into the solution test was done. The MR tests had done in a 100 ml aptitude glass beaker positioned in a water thermostat, which enclosed 100 ml of 1 M nitric acid with and without various doses of PEG. After 3 hours inundation, the coins had been obtained, washed, dried, and massed exactly. The mean MR of the all α-brass coins can be obtained from the relation:

\[ \Delta W = W_B - W_A \]

where \( W_B \) and \( W_A \) are the mass of α-brass before and after coming into contact with the destructive solution, correspondingly. The %IE and the degree of surface coverage (\( \theta \)) of PEG for the corrosion of α-brass were computed as follows:

\[ \text{%IE} = \theta \times 100 = \left[ 1 - \left( \frac{\Delta W_{\text{free}}}{\Delta W_{\text{inh}}} \right) \right] \times 100 \]

where \( \Delta W_{\text{free}} \) and \( \Delta W_{\text{inh}} \) are the mass losses of α-brass per unit area with and without of PEG correspondingly.

\[ \text{C.R.} = \frac{\Delta W}{ADT} \]

where C.R. is the rate of corrosion in (mg cm\(^{-2}\) min\(^{-1}\)) and \( D \) is metal density (g cm\(^{-3}\)).

2.3.2. Potentiodynamic polarization tests

PP investigations were done in a predictable three-electrode cell. The working electrode (WE) was cut from α-brass coins of equal conformation implanted in epoxy resin. Prior to each measurement, the electrode surface was pretreated in the similar way as the MR tests. The potential was taking place from -600 to +400 mV vs open circuit potential (E\(_{\text{ocp}}\)). All tests were done in freshly ready solutions at 25 ± 1°C.

2.3.3. Impedance tests

EIS tests were carried out by utilizing AC signals of 5 mV peak-to-peak amplitude at the OCP in the frequency of 100 kHz to 0.1 Hz. All EIS data were fitted to suitable equivalent circuit using the Gamry Echem Analyst software. The %IE and the (\( \theta \)) of the PEG obtained from the EIS can be measured from Equation (4) (38):

\[ \text{%IE} = \theta \times 100 = \left[ 1 - \left( \frac{R_{\text{ct}}}{R_{\text{ct}}} \right) \right] \times 100 \]

where \( R_{\text{ct}} \) is the resistance in the lack and attendance of inhibitor, correspondingly.

2.3.4. Electrochemical frequency modulation tests

EFM was done with relating potential perturbation signal with an amplitude of 10 mV with two sine waves of 2 and 5Hz (39). The greater peaks have utilized to calculate the EFM parameters (40).

All electrochemical tests were done at 25±1°C, utilizing Gamry apparatus PCI300/4 Potentiostat/Galvanostat/Zra analyzer.

2.3.5. Surface analysis

The α-brass coins were inundated in numerous test solutions. Then, they have engaged out and dried. The natural surroundings of the film formed on the α-brass surface coins were measured by FT-IR utilizing a
Spectrum RXI Spectrophotometer, by SEM utilizing a VEGA3-TESCAN model, and by AFM using A100 model (A.P.E Research, Italy).

3. Results and discussion

3.1. Potentiodynamic polarization tests

Nitric acid is a strong oxidizer for α-brass (41). From the Tafel polarization diagrams, there is no steep slope in the anodic range, indicating that no passive films are obtained on the surface α-brass. PP test was carried out in order to gain information regarding the kinetics of the cathodic and anodic reactions (42). Figure 1 displays the PP performance of α-brass in 1 M HNO3 with and without various doses of PEG. The results of PP: $i_{corr}$ (corrosion current densities), $E_{corr}$ (corrosion potential), cathodic and anodic Tafel slopes ($\beta_a$, $\beta_c$), (θ), and (% IE) were measured from the diagrams of Figure 1 and are recorded in Table 1 for PEG.

The results in Table 1 revealed that there is a small change in the values of cathodic and anodic reactions by adding various doses of PEG, meaning that the addition of PEG lower the anodic dissolution of α-brass and also impedes the cathodic reactions. In the presence of PEG, $E_{corr}$ was improved with no certain trend, indicating that PEG acts as a mixed-kind inhibitor in 1 M HNO3. The $i_{corr}$ lowered clearly after the adding of PEG in 1 M HNO3 and % IE rises with increasing the PEG doses. % IE and the (θ) can be obtained from Equation (5):

$$\%IE = \theta \times 100 = \left[ \frac{i_{corr} - i_{corr(inh)}}{i_{corr}} \right] \times 100$$

where $i_{corr}$ and $i_{corr(inh)}$ are the corrosion current densities without and with PEG, correspondingly. As indicated from Table 1, (i) the exchange in $\beta_a$ values among the inhibitor-containing systems and the blank are higher than that of $\beta_a$ which designates that PEG but mainly inhibits cathodic reactions, even though anodic dissolution of α-brass is also protected (mixed-type one) and (ii) the $i_{corr}$ data decreased by the addition of PEG. Thus increasing PEG doses lowers the dissolution of α-brass and retards the cathodic. Thus the adsorbed PEG acts by simple hindering of the active center for both cathodic and anodic centers. Other words, PEG decreased the surface area available for anodic dissolution and oxygen reduction reactions.

3.2. Impedance tests

Figure 2 displays the Nyquist diagrams obtained for the α-brass in 1 M HNO3 with and without various doses of PEG at 25°C. As the PEG dose increases, the semicircle diameter improves. The deviation from ideal semicircle was generally attributed to the frequency dispersion as well as to the inhomogeneities of the surface (43). EIS data of the examined PEG were measured utilizing the equivalent circuit, Figure 3, which signifies a single charge transfer reaction and fits well with our experimental data. The constant phase element, CPE, is presented in the circuit in its place of a pure double layer capacitor to provide a more accurate fit (44). The $C_{dl}$ for a circuit excluding a CPE parameter ($\gamma^0$ and n) was measured from Equation (6) (45):

$$C_{dl} = \frac{\gamma^0 n^{-1}}{\sin[\pi n/2]}$$

where $\gamma^0$ is the magnitude of the CPE; $\omega = 2\pi f_{max}$, $f_{max}$ is the frequency maximum. The semicircle diameter signifies the $R_{ct}$, corresponding to the polarization resistance, $R_p$ and inversely proportional to the $i_{corr}$ data. Rise in $R_{ct}$ was due to rise in the thickness of the double layer that adsorbed by molecules of PEG (46). In addition, the value of the $C_{dl}$ was lowered by increasing PEG dose. Furthermore, $C_{dl}$ can be measured from Equation (7):

$$C_{dl} = \frac{\varepsilon \varepsilon_0}{\delta}$$

where $\varepsilon$ is the dielectric double-layer constant, $\varepsilon_0$ the permittivity vacuum electrical, and δ the thickness double

| $[\ln(h)]$ | $E_{corr}$, V vs. SCE | $i_{corr}$, $\mu$A cm$^{-2}$ | $\beta_a$, mV dec$^{-1}$ | $\beta_c$, mV dec$^{-1}$ | C.R. mpy | θ | %IE |
|----------|---------------------|-----------------|-----------------|-----------------|---------|---|-----|
| Blank    | 0.003               | 1270            | 119             | 199             | 1222.2  | – | –   |
| 50       | 0.029               | 960             | 93              | 200             | 923.8   | 0.244 | 24.4 |
| 100      | 0.038               | 884             | 92              | 224             | 850.5   | 0.304 | 30.4 |
| 150      | 0.062               | 789             | 91              | 161             | 759.7   | 0.378 | 37.8 |
| 200      | 0.061               | 618             | 90              | 157             | 594.8   | 0.513 | 51.3 |
| 250      | 0.062               | 384             | 74              | 150             | 369.6   | 0.698 | 69.8 |
| 300      | 0.047               | 248             | 83              | 155             | 238.8   | 0.805 | 80.5 |

Figure 2. EIS Nyquist diagrams for α-brass in 1 M HNO3 with and without different doses of PEG 25°C.

Figure 3. Circuit equivalent utilized to EIS data.
layer. Mainly, the lower value of $C_{dl}$ was due to the replacement of the adsorbed water molecules at the $\alpha$-brass surface by the PEG molecules having lower dielectric constant. The EIS parameters were recorded in Table 2. The IE and $\theta$ were measured from the $R_{ct}$ data from Equation (4).

### 3.3. EFM tests

The advantages of EFM are: (i) nondestructive test, (ii) presence of causality factors which help as an inner check on the strength of EFM test, and (iii) directly given the $i_{corr}$ data without prior information of $\beta_a$ and $\beta_c$ this makes it an ideal applicant for online corrosion checking (47). Figure 4 displays the EFM spectra of $\alpha$-brass in nitric acid solution enclosing various doses of PEG. Each spectrum is a current reply as a function of frequency (48). The greater peaks were utilized to measure EFM parameters, which is recorded in Table 3. The $%I_{EFM}$ and $\theta$ rise by improving the PEG dose were measured from Equation (5).

### 3.4. MR measurements

The MR of the $\alpha$-brass specimen in 1 M HNO$_3$ solution with and without various doses from the PEG was measured after 3 hours of dipping at 25 $\pm$1°C. Figure 5 signifies this for PEG. Obtained values of $%I_{E}$ and $\theta$ were given in Table 4 at different doses from the PEG. The detected protection action of PEG could be qualified to the adsorption on the $\alpha$-brass surface (49). The data obtained displayed that the appending of PEG decreased the WL (mg cm$^{-2}$) and the C.R. (mg cm$^{-2}$ min$^{-1}$). The ($%I_{E}$) and ($\theta$) of PEG for the corrosion of $\alpha$-brass were measured from Equation (2).

### 3.5. Effect of temperature

It was found that the IE decreases with raising temperature but at lower rate than in unprotected solutions with increasing the dose of the PEG, as exposed in Table 5. The values of this table illustrate that the adsorption decreases with an increasing in temperature, and corrosion rate ($k_{corr}$) increases. Indicating that raising of temperature leads to the reduction of the PEG adsorption and then accelerate the dissolution process, so the adsorption behavior of PEG on the $\alpha$-brass surface in 1 M HNO$_3$ occurs through physical adsorption. The decrease of % IE with increasing the temperature an indication for the physical adsorption.

![Figure 4. EFM spectra for $\alpha$-brass in 1 M HNO$_3$ with and without unlike doses of PEG at 25°C.](image-url)
3.6. Kinetic–thermodynamic corrosion parameters

The energy of activation \( E_a^\ast \) of the corrosion procedure was measured utilizing Arrhenius equation (8) (50):

\[
k_{corr} = A \exp \left( \frac{-E_a^\ast}{RT} \right)
\]

where \( A \) is Arrhenius constant and \( E_a^\ast \) is the data of activation energy. The values of \( E_a^\ast \) can be obtained from the slope of the straight lines of drawing \( \log k_{corr} \) vs. \( 1/T \) with and without various doses of PEG at various temperatures (Table 6). Figure 6 shows the linear regression \( R^2 \) is close to 1, which indicates that the corrosion of \( \alpha \)-brass in 1 M HNO\(_3\) solution can be explained by utilizing the kinetic model (Table 6). The effective \( E_a^\ast \) displays greater data in the presence of PEG than in its absence. Therefore, PEG delays the corrosion procedure at minor temperatures but this protection action is lowered at upper temperature. Also, an increase in \( E_a^\ast \) with the presence of PEG designates that the energy barrier for the corrosion reaction was improved. Since these values of \( E_a^\ast > 40 \text{ kJ mol}^{-1} \), the metal dissolution reaction is diffusion controlled. The activation in the blocking of the active sites must be associated with a rise in the \( E_a^\ast \) of \( \alpha \)-brass corrosion in the inhibited state (51). The \( E_a^\ast \) for the corrosion of \( \alpha \)-brass in 1 M HNO\(_3\) was found to be 32 kJ mol\(^{-1}\), which is in best agreement with the work accepted by Fouda et al. (52) and others (53). Enthalpy and entropy of activation (\( \Delta H^\ast \), \( \Delta S^\ast \)) are measured from transition state theory utilizing Equation (9):

\[
k_{corr} = \frac{RT}{Nh \exp \left( \frac{\Delta S^\ast}{R} \right) \exp \left( -\frac{\Delta H^\ast}{RT} \right)}
\]

where \( h \) is Planck’s constant. Figure 7 displays diagrams of \( \log (k_{corr}/T) \) vs. \( 1/T \). Straight lines were obtained with linear regression \( R^2 \) close to unity from which the data of \( \Delta H^\ast \) and \( \Delta S^\ast \) were measured and also recorded in Table 6.

In Table 6, the negative values of \( \Delta H^\ast \) indicates that the dissolution process at the activated state is exothermic (54). The rise in the \( \Delta H^\ast \) in the presence of the PEG means that the rise in the height of the energy barrier of the corrosion reaction to an extent relies on the dose of PEG. The adsorption of PEG on the metal surface leads to a reduction

| Conc, ppm | 25°C | 30°C | 35°C | 40°C | 45°C |
|-----------|------|------|------|------|------|
| Blank k\( \text{corr, (mg cm}^{-2} \text{ min}^{-1}\) | 0.663 | 0.678 | 1.092 | 1.109 | 2.069 |
| 50 \( \theta \) | 0.491 | 0.485 | 0.303 | 0.260 | 0.175 |
| \% IE | 49.1 | 48.5 | 30.3 | 26.0 | 17.5 |
| 100 \( \theta \) | 0.338 | 0.349 | 0.761 | 0.821 | 1.706 |
| \% IE | 78.1 | 73.6 | 48.1 | 45.2 | 24.3 |
| 150 \( \theta \) | 0.145 | 0.179 | 0.567 | 0.607 | 1.566 |
| \% IE | 88.0 | 77.7 | 61.7 | 59.4 | 33.7 |
| 200 \( \theta \) | 0.079 | 0.151 | 0.419 | 0.450 | 1.371 |
| \% IE | 89.6 | 87.8 | 65.2 | 64.0 | 44.9 |
| 250 \( \theta \) | 0.060 | 0.083 | 0.380 | 0.399 | 1.140 |
| \% IE | 90.9 | 89.6 | 68.8 | 65.5 | 49.0 |
| 300 \( \theta \) | 0.060 | 0.071 | 0.340 | 0.382 | 1.056 |
| \% IE | 91.9 | 91.7 | 70.1 | 69.6 | 55.5 |
| 300 ppm k\( \text{corr, (mg cm}^{-2} \text{ min}^{-1}\) | 0.054 | 0.056 | 0.327 | 0.337 | 0.920 |

Table 3. Parameters obtained by EFM test for \( \alpha \)-brass with and without various doses of PEG in 1 M HNO\(_3\) at 25°C.

| \[\ln(h)\] ppm | \(k_{corr, 2} \text{ A cm}^{-2}\) | \(\beta_a \text{, mV dec}^{-1}\) | \(\beta_c \text{, mV dec}^{-1}\) | CF-2 | CF-3 | C.R. mpy | \(\theta\) | \%IE |
|---------------|-----------------|-----------------|-----------------|-------|-------|---------|------|------|
| 0 | 457.2 | 172 | 92 | 1.01 | 2.48 | 440.7 | – | – |
| 50 | 295.3 | 128 | 129 | 1.96 | 3.18 | 284.5 | 0.354 | 35.4 |
| 100 | 252.7 | 117 | 153 | 1.85 | 2.18 | 243.6 | 0.447 | 44.7 |
| 150 | 133.7 | 81 | 150 | 1.92 | 2.79 | 128.9 | 0.707 | 70.7 |
| 200 | 107.4 | 69 | 124 | 1.91 | 2.75 | 103.5 | 0.765 | 76.5 |
| 250 | 80.3 | 64 | 114 | 1.90 | 3.38 | 77.43 | 0.824 | 82.4 |
| 300 | 67.6 | 72 | 138 | 1.86 | 2.97 | 65.2 | 0.852 | 85.2 |

Figure 5. MR-time diagrams for the dissolution of \( \alpha \)-brass with and without various doses of PEG at 25°C.

**Table 4.** % IE of PEG at 180 min for \( \alpha \)-brass in 1 M HNO\(_3\) solution with and without different doses as determined from MR method at 25°C.

| \[\ln(h)\] ppm | \(\theta\) | \%IE |
|---------------|------|------|
| 0.0 | – | – |
| 50 | 0.491 | 49.1 |
| 100 | 0.781 | 78.1 |
| 150 | 0.880 | 88.0 |
| 200 | 0.896 | 89.6 |
| 250 | 0.909 | 90.9 |
| 300 | 0.919 | 91.9 |

**Table 5.** Values of %IE, \( \theta \) and \( k_{corr} \) from MR measurements for \( \alpha \)-brass corrosion after 180 min immersion in 1 M HNO\(_3\) with and without various doses of PEG at different temperatures.
in $k_{corr}$ because of the blocking of the surface of the metal by adsorbed molecules of the PEG. The data of $\Delta S$ with and without PEG are small and negative sign; this specifies that the activated complex in the rate-determining step prefers association rather than dissociation step, meaning that a lowering in disordering occurred upon going from reactants to the activated complex ($55, 56$).

### 3.6.3 Adsorption isotherms

Adsorption isotherms were done to fit ($\theta$) values to various adsorption isotherms ($57, 58$). The Langmuir adsorption isotherm ($59$) was found to fit well the investigated data.

$$\frac{C}{\theta} = \left( \frac{1}{K_{ads}} \right) + C$$  \hspace{1cm} (11)

where $K_{ads}$ is constant adsorption equilibrium. A plot of $C/\theta$ against $C$ gives straight lines with slope of approximately equal unity and the intercept is equal $1/K_{ads}$. In order to get a comparative view, the variation of the adsorption equilibrium constant ($K_{ads}$) of the inhibitor with its molar dose was measured according to Equation (11). The obtained values give best diagrams fitting for the practical adsorption isotherm.

Equation (12) could be used to calculate the free energy of adsorption ($\Delta G_{ads}^0$):

$$\log K_{ads} = \frac{-\log(55.5 - \Delta G_{ads}^0)}{2.303RT}$$  \hspace{1cm} (12)

where 55.5 is the molar dose of water in the bulk solution in mol L$^{-1}$. We can measure other thermodynamic parameters such as heat of adsorption ($\Delta H_{ads}^0$) and the standard entropy ($\Delta S_{ads}^0$) by drawing $\log K_{ads}$ vs $1/T$ in (Figure 8) conforming to the thermodynamic basic equations (13, 14).

$$\log K_{ads} = \frac{-\text{constant} - \Delta H_{ads}^0}{2.303RT} \hspace{1cm} (13)$$

$$\Delta G_{ads}^0 = \Delta H_{ads}^0 - T\Delta S_{ads}^0 \hspace{1cm} (14)$$

The data of thermodynamic parameters for the adsorption of PEG from Langmuir isotherm were measured at 25–45°C and were verified in Table 7, which can provide appreciated material about the mechanism of corrosion protection. As the absolute data of $\Delta H_{ads}^0$ obtained in this study were lower than 80 kJ mol$^{-1}$, this is suggestive of physical adsorption ($55, 60$) (Figure 9).

The measured data of $\Delta G_{ads}^0$ are around 14–18 kJ mol$^{-1}$ and the absolute data of $\Delta H_{ads}^0$ obtained in this study were less than 80 kJ mol$^{-1}$, which represents that the adsorption is physisorption. The entropy of
adsorption obtained is large and negative because PEG molecules cannot be freely moving in the bulk solution, and were adsorbed in an orderly manner onto the α-brass, resulting in a decrease in entropy (61). Moreover, from thermodynamic principles, since the adsorption was an exothermic process, it must be accompanied by a lower entropy (62). Also, this is confirmed from the PEG compared with its absence. The higher values of $K_{ads}$ for PEG indicate stronger adsorption on the α-brass surface in 1 M HNO$_3$ solution.

### 3.8. Surface tests

#### 3.8.1. SEM test

Figure 10 signifies the micrograph of α-brass samples before and after dipping in 1 M HNO$_3$ for 1 day. It is clear that α-brass alloy surfaces suffer from severe decomposition attack (Figure 10(b)). Figure 10(c) represents the surface of α-brass alloy after coming in contact with 1 M HNO$_3$ solution, including 300 ppm PEG. It is significant to stress out that when the composite is present in the solution, the morphology of α-brass alloy surfaces is quite unlike from the preceding one, the picture of the surface was smoother, due to the adsorbed formed film on the α-brass alloy.

#### 3.8.2. AFM analysis

AFM is a dynamic tool to inspect the surface morphology from nano to microscale. The 2D and 3D AFM pictures of polished α-brass, α-brass immersed in 1 M HNO$_3$ after 24 h and α-brass immersed in 1 M HNO$_3$+ 300 ppm PEG after 24 h, are presented in Figure 11(a–c). As can be seen from the AFM images, the surface is very clear for polished α-brass (Figure 11(a)), whereas in α-brass dipped in 1 M HNO$_3$ (Figure 11(b)), the surface is severely scratched by the corrosive solution. In (Figure 11(c)), the surface is inhibited from attack by the adsorbed layer formed by the PEG molecules. AFM data for α-brass are given in Table 8.

#### 3.8.3 FT-IR analysis

The FT-IR spectrum of pure PEG solution is shown in Figure 12(a). The broad absorption peak at 3332 cm$^{-1}$ shows OH stretching vibration. The FT-IR spectrum of the film formed on the surface of the α-brass after dipping in solution containing 300 ppm of PEG is shown in Figure 12(b), the OH stretching frequency appeared at 3356 cm$^{-1}$. This change is instigating by the electron cloud density from the O atom to α-brass. This recommends that the O atom of the PEG is coordinated to α-brass (Cu$^{2+}$, Zn$^{2+}$), resulting in the creation of adsorbed layer on the α-brass surface. The peak at 1652 cm$^{-1}$ is C–C stretching of alkene non-conjugated on the surface film that increased from 1633 cm$^{-1}$ of pure PEG.

### 4. Conclusion

PEG is good corrosion protection for α-brass in 1 M HNO$_3$ solution. The adsorption of PEG depends on its doses,

| $T$, K | $K_{ads}$, M$^{-1}$ | $-\Delta G_{ads}$, kJ mol$^{-1}$ | $-\Delta H_{ads}$, kJ mol$^{-1}$ | $-\Delta S_{ads}$, J mol$^{-1}$ K$^{-1}$ |
|-------|-----------------|-------------------------------|-------------------------------|----------------------------------|
| 298   | 23.6            | 17.8                          | 69.8                          | 174.56                           |
| 303   | 19.0            | 17.5                          | 172.47                        |
| 308   | 10.0            | 16.2                          | 174.18                        |
| 313   | 8.0             | 15.9                          | 172.34                        |
| 318   | 3.5             | 14.0                          | 175.57                        |

Figure 9. Plots of log $K_{ads}$ vs. 1/T for the adsorption of PEG on α-brass in 1 M HNO$_3$.

Figure 10. SEM portraits of α-brass surface: (a) polished α-brass before of inundation in 1 M HNO$_3$, (b) after 24 h of inundation in 1 M HNO$_3$ and (C) after 24 h of inundation in 1 M HNO$_3$+ 300 ppm PEG.
temperatures, and the nature of the drug and metal. EFM can be utilized as a fast and nondestructive test for corrosion analysis without prior information of Tafel slopes.

The EIS results exposed that a rise in the $R_{ct}$ and a lower in $C_{dl}$ when added PEG and hence an improve in %IE. This is due to rise of the thickness of the electrical

**Figure 11.** 2D and 3D AFM of α-brass: (a) polished α-brass before of inundation in 1 M HNO$_3$, (b) after 24 h of inundation in 1 M HNO$_3$ and (C) after 24 h of inundation in 1 M HNO$_3$ + 3 00 ppm PEG.
double layer. The outcome data obtained from PP designated that the PEG is a mixed-kind inhibitor. The adsorption of PEG on surface of $\alpha$-brass follows the Langmuir isotherm model. The results of the SEM and AFM studied showed that the surface smoothness increases in the existence of PEG due to the formation of a protective surface film. The results obtained from and non-electrochemical tests were in excellent agreement.

Disclosure statement
No potential conflict of interest was reported by the authors.

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