Virtual corrosion testing on stainless steel AISI 304 welded pipe with Hydroxyethyl Cellulose in 3.5% NaCl solution and turbulent flow

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Abstract

A virtual corrosion testing machine is used to investigate the corrosion inhibition efficiency and mechanism of an inhibitor in stainless-steel 304 pipes under turbulent flow conditions. The pipes are welded by the gas tungsten arc welding method and evaluated in 3.5 percent sodium chloride solution with absence (0 ppm) and presence 100, 300, and 600 ppm hydroxyethyl cellulose concentrations. The solutions are absence and presence the inhibitor, are fed in the welded pipe at a flow rate of 7,500 and 15,000 cm³ per minute as behaves to be turbulent flows. Electrochemical impedance spectroscopy and potentiodynamic polarization techniques are used to investigate the corrosion inhibition process. The inhibitor can adsorp on the surface of stainless steel welded pipe and inhibit the corrosion rate of the stainless steel. The concentration volumes of the inhibitor are correlating the corrosion rate in the same direction. The turbulent flow is to reduce the adsorption mechanism of the inhibitor, affect to corrosion reaction for the stainless-steel welded pipe and relate to the corrosion rate. If the flow rate increases, the corrosion rate would also increase. The corrosion inhibition efficiency is reached up to 66% by addition HEC 600ppm concentration in the condition. Pitting corrosion is observed on the heat-affected zone of the welded pipe by scanning electron microscope.

1. Introduction

Rust looks like cancer for metal materials, and it has been much cost for many industries. The United States (U.S.) has released a report of metallic corrosion costs study from the year 1999–2001 which has been conducted by CC Technologies Laboratories, Inc., with support from the FHWA and NACE. The study results show that the total annual estimated direct corrosion cost in the U.S. was $276 billion or approximately 3.1 percent of the gross domestic product (GDP) of the year 1998 [1]. So the corrosion should be inhibited or prevented before occurring of the rust. Stainless steel AISI 304 pipe is widely used in high temperature, and corrosive service due to it contains 8–11 percent Ni for corrosive resistance and 18–20 percent Cr for oxidation resistance at a high temp [2–4]. Although it is suitable for highly corrosive environments such as a coolant pipe in marine applications, the metal substrate has exposed from corrosion processes. The especially welding area that has been taken some heat input to join the pipes [5, 6]. The pitting corrosion is a problem for stainless steel AISI 304 at the end of the welding process due to chromium carbide precipitation [7–10].

Corrosion inhibitors are widely used and a great practical implementation to inhibit corrosion process for steel in acidic media. Corrosion protection is using corrosion inhibitors by adding a small amount of chemicals to the solution to reduce the surface corrosion of metallic materials [11–14]. The method is one of the most commonly used for pipe applications and the petroleum industry [15–17]. The inhibitor can reduce the rate of oxidation or reduction or both. This reduction may be due to the formation of a protective film of the corrosion inhibitor covering the surface of the metal from using an anodic or cathodic corrosion inhibitor. Anodic corrosion inhibitor causes an increase in anodic polarization, and the electric potential of the metal is shifted more positively and reduces oxidation reaction. Cathodic corrosion inhibitors affect the system in contrast to
anodic corrosion inhibitors, and it reduces the reduction reaction \([18, 19]\). Hydroxyethyl cellulose is generated from cellulose, so it is non-toxic, cheap, eco-friendly corrosion inhibitor, and convenient to be provided from the online market. It is being used in many applications especially corrosion inhibition in the metal materials such as mild steel in hydrochloric acid \([20]\), 1018 c-steel in sodium chloride \([21]\) and copper in hydrochloric acid \([22]\).

Electrochemical techniques are a popular method to investigate corrosion mechanisms and calculate the corrosion rate. \(E_{\text{corr}}\) versus Time technique is a technique used to measure the electric potential of a sample metal in an electrolyte solution by measuring the electrical potential of the reference electrode. The sample metal in the electrolyte solution is subjected to a spontaneous reaction, showing the corrosion potential of the sample metal. Tafel plot technique is measurement corrosion currents \(i_{\text{corr}}\) are used to calculate the corrosion rate and able to be obtained from the slope of the Tafel curve \(\beta_{\text{p}}\) and \(\beta_{\text{c}}\) \([23]\). Potentiodynamic polarisation technique for analysing the corrosive behaviour of the sample metal in the environment \([24]\). Specifically, the sample metal has properties in form active-passive or protective film. Electrochemical impedance spectroscopy can study corrosion resistance of metallic alloys with coatings which are investigated using the combined impedance spectroscopy of the electrochemical cell system of the test as referring to ASTM G3 and ASTM G5 for the testing method standard. Nyquist \(-Z''\) versus \(Z'\) plots as the term of \(Z'\) is real part and \(Z''\) is imaginary part of impedance \([15, 25\text{–}27]\).

Turbulent flow or disorderly flow is a form of flow, which fluid particles move disorderly with uncertain directions. The flow direction is unpredictable, and there is a mixture of fluid layers while the fluid is flowing. The flow characteristics generally occur with low viscosity fluids, high velocity and the small diameter of the pipe \([28]\). The Reynolds number \(\text{Re}\) is a numerical value indicating the laminar flow or turbulent flow for pipe fluids \([29, 30]\). If the \(\text{Re} < 2000\), \(2000 \leq \text{Re} \leq 4000\) and \(\text{Re} > 4000\), the flows are laminar flow, transition flow and turbulent flow, respectively \([31, 32]\).

This study objects to investigate the mechanism of the corrosion inhibitors on stainless steel 304 welded pipes with gas tungsten arc welding in 3.5 percent sodium chloride solution under two turbulent flow rate by using a virtual corrosion testing machine. The materials have been investigated using electrochemical impedance spectroscopy, potentiodynamic polarization, Tafel plot techniques under turbulent flow condition. And scanning electron microscope is observed surface and corrosion damage pattern.

### 2. Materials and methods

#### 2.1. Stainless steel pipe

The pipe is austenitic stainless steel AISI 304. Wall of the pipe is thickness 2.77 mm, outer diameter 21.3 mm and length 6 metres (Referring to ASTM no. A 312, grade TP304, stainless steel pipe size: DN15 or NPS1/2) as referring to the chemical composition of the stainless steel AISI 304 pipe is shown in table 1.

#### 2.2. Welding wire and tungsten electrode

The welding wire is ER 308L and diameter 2.4 mm as referred to ANSI/AWS A5.9–06 standard and chemical composition of the welding wire is shown in table 2. The tungsten electrode is thoriated tungsten (EWTh-2) as applied to ASTM A790/A790M-16 and ANSI/AWS A5.12M/A5.12-09 standards.

| Table 1. Chemical composition of the stainless steel AISI 304 pipe (ASTM A312/A312M-2017). |
|-----------------|-----------------|-----------------|
| Element        | Requirement of ASTM A312/A312M-17 | Result         |
| C              | 0.080 max       | 0.031          |
| Mn             | 2.000 max       | 1.262          |
| P              | 0.045 max       | 0.021          |
| S              | 0.030 max       | 0.004          |
| Si             | 1.000 max       | 0.434          |
| Cr             | 18.000–20.000   | 18.400         |
| Ni             | 8.000–11.000    | 8.202          |
| Fe             | Balance         | 71.606         |

The welding wire is ER 308L and diameter 2.4 mm as referred to ANSI/AWS A5.9–06 standard and chemical composition of the welding wire is shown in table 2. The tungsten electrode is thoriated tungsten (EWTh-2) as applied to ASTM A790/A790M-16 and ANSI/AWS A5.12M/A5.12-09 standards.
2.3. Corrosion inhibitor

Hydroxyethyl cellulose (HEC) is CAS number 9004-62-0. The chemical formula of HEC is $C_6H_7O_2(OH)_{3-x} \{OCH(OH)CH_3\}_x\{H_2O\}$, as seen in figure 1. The HEC powder is obtained and tested from Daejung, as seen in table 3.

2.4. Welding

The stainless steel AISI 304 pipes are cut to be length 50 mm. And they are joined by using gas tungsten arc welding (GTAW) process with 100 percent argon gas as the shielding gas and using welding wire ER 308L. The mean direct current value of the welding is 70 ampere. After completion of the welding process, and the samples are cooled in the air.

2.5. Stainless steel 304 welded Pipe's surface cleaning

Take the specimens in a beaker and immerse in the gel (KOVET: KV-501) to bite rust and contamination on the metal and welding surface area by soaking the samples for five minutes, then wash in ethanol, distilled water, wipe with a dry cloth and hot air blowing respectively. As referring to a specimen which is before and after cleaned in figure 2.
2.6. Passivation treatment process
Passivation treatment in Nitric acid solutions as followed ASTM 967/A967M-17. Stainless steel parts shall be treated in the following Nitric aqueous solutions which shall contain 25 volume percent of nitric acid. The components shall be immersed for a minimum of 30 min at a temperature in the range from 21 to 32 °C. Hold the pipe sample in normal air more than 24 h before testing.

2.7. Sodium chloride solution with inhibitors
Prepare sodium chloride (NaCl) solution at concentration 3.5 percent by weight (wt%) for deionized water volume 30,000 cm³ into the solution container of virtual corrosion testing equipment. The inhibitors are dissolved in water and filled in 3.5 wt% NaCl as the corrosive solution at 100 ppm, 300 ppm and 600 ppm as the chemical concentrations and volumes in table 4 into solution container of virtual corrosion testing equipment.

2.8. Machine and equipment
Electrochemical measurements are performed in a conventional three-electrode cell by using potentiostat/galvanistat autolab model: PGSTAT302N and FRA/GPES software. Then connect the wires from working electrode (WE), counter electrode (CE) and reference electrode (RE) to the potentiostat/galvanistat equipment. Silver/silver chloride (Ag/AgCl) is used as the reference electrode, platinum rode is used as a counter electrode, and the stainless steel 304 welded pipe is working electrode as see figure 3.

2.9. Testing
Then turn on the system and set the solution flow rate at 7,500 or 15,000 cm³ per minutes. Then run Fra program and set parameters in the frequency range 100,000–0.01 Hz for electrochemical impedance technique to find corrosion resistance data in term of Nyquist –$Z''$ versus $Z'$ plots. And find out the best equivalent electrical circuit models are a match with the plot. Then fitting the plot is with the models. Run GPES program to test $E_{corr}$ versus time, potentiodynamic polarisation by using the potentials range from $-0.25$ V to 1.2 V at a scan rate 0.001 V s⁻¹. Tafel plot technique is to find corrosion potential ($E_{corr}$), corrosion current ($I_{corr}$) and corrosion rate (um/year). The efficiency of an inhibitor can be calculated as the following equation (1) [16, 12, 33, 34].

![Figure 2. The specimen (a) before and (b) after the surface cleaning process.](image)

![Figure 3. Virtual Corrosion Testing: (a) Virtual corrosion testing with flow direction of the solution; (b) Virtual corrosion testing model and (c) A pipe specimen with connected electrodes: (1) Reference Electrode [Ag/AgCl]; (2) Working Electrode and (3) Counter Electrode [Platinum].](image)

| Chemical name                          | Chemical formula                          | Concentration | Volume   |
|----------------------------------------|-------------------------------------------|---------------|----------|
| Sodium Chloride                        | NaCl                                      | 3.5%wt        | 1,050 g  |
| Hydroxyethyl Cellulose (CAS# 9004-62-0) | $[\text{C}_6\text{H}_7\text{O}_2\text{(OH)}_{3-x}\{\text{OCH(OH)CH}_3\}_x]_n$ | 100 ppm       | 3 g      |
|                                        |                                           | 300 ppm       | 9 g      |
|                                        |                                           | 600 ppm       | 18 g     |

Table 4. Chemical concentration for evaluation in each condition.
Inhibitor efficiency (IE) % = \frac{CR_{\text{blank}} - CR_{\text{inhibitor}}}{CR_{\text{blank}}} \times 100\%

(1)

where \(CR_{\text{blank}}\) and \(CR_{\text{inhibitor}}\) are the corrosion rate without and with inhibitor, respectively.

The surface coverage \(\theta\) value can be calculated in term of IE data as following equation (2) [21, 33].

\[ \theta = \frac{\text{IE}}{100} \]

(2)

The Reynolds (Re) is a number for determining the flow conditions and calculated by the equation (3) below.

[\text{Re} = \frac{vD}{\nu}]  

(3)

Where \(v\), \(D\) and \(\nu\) are fluid velocity (m s\(^{-1}\)), the inner diameter of the pipe (m) and kinematic viscosity of the fluid (m\(^2\) s\(^{-1}\)), respectively [35, 36].

Calculated results for the Reynolds number of flow rate 7,500 cm\(^3\) min\(^{-1}\) is \(\text{Re}_{(7,500)}\) equal to 12,612 and flow rate 15,000 cm\(^3\) min\(^{-1}\) is \(\text{Re}_{(15,000)}\) equal to 25,224. Re of both flow rates are more than 4,000, so both flow behaviours are turbulent flow [36, 37].

3. Results and discussion

3.1. Corrosion resistance testing using electrochemical impedance spectroscopy technique

The performance of HEC as corrosion inhibitor at stainless steel 304 welded pipe in 3.5 wt% NaCl solution has studied adsorption phenomena and mechanism of HEC inhibitor by electrochemical impedance spectroscopy (EIS) and fitting to the equivalent electrical circuit models [37, 38].

3.1.1. Electrochemical impedance spectroscopy

The performance of the inhibitors extract at the stainless steel 304 welded pipe in 3.5 wt% NaCl solution is studied by electrochemical impedance spectroscopy technique. The figures 4 and 5 shows the Nyquist –\(Z''\) versus \(Z'\) plots of stainless steel 304 welded pipe in 3.5 wt% NaCl with various HEC inhibitor concentration under flow rate 7,500 and 15,000 cm\(^3\) min\(^{-1}\), respectively.

The Nyquist plots in figures 4 and 5 show a single capacitive loop and not perfect semicircles in every HEC concentration due to inhibitor’s adsorption, surface roughness or porous layers [21, 39]. The capacitive loop diameter of 600 ppm HEC inhibitor concentration is larger than lower HEC inhibitor concentration. While the capacitive loop diameter is the solution without inhibitor is the smallest. The addition of HEC inhibitor concentration further causes an increase in the capacitive loop diameter, which is in the ordering to 0 ppm < 100 ppm < 300 ppm < 600 ppm.

The comparison of Nyquist –\(Z''\) versus \(Z'\) plots between flow rate 7,500 and 15,000 cm\(^3\) min\(^{-1}\) of stainless steel 304 welded pipe in 3.5 wt% NaCl with 0 and 600 ppm HEC inhibitor concentrations are shown in figure 6.

The Nyquist plots in figure 6 show that the flow rate or turbulent flow is increased from 7,500 to 15,000 cm\(^3\) min\(^{-1}\); the capacitive loop is increased. When the HEC inhibitor concentration is increased from 0 to 600 ppm, the capacitive loop is also increased. Thus the HEC concentration and turbulent flow are affected by the...
capacitive loop of stainless steel 304 welded pipe in 3.5 wt% NaCl. The capacitive loop is increasing or decreasing in the same direction as the concentration of the HEC inhibitor and the flow rate [21].

3.1.2. Equivalent electrical circuit
The two equivalent electrical circuit models are generated for using to fit the EIS data of each inhibitor concentration conditions, as shown in figure 7 [40]. The circuit models have been created from trial and error with the EIS data based on chi-square values ($\chi^2$) and represent the physical system. The selected circuit models are the available smallest chi-square value for with and without HEC inhibitor conditions [41].

Both equivalent electrical circuit models are consists of seven parameters, where are $R_s$, $R_{ct}$, $R_h$, $R_p$ and $R_m$ represent to solution resistance, charge transfer resistance, inhibitor resistance, passivation resistance and metal resistance. $C_1$, $C_2$ and $C_3$ are represented to charge transfer capacitance, passivation capacitance and metal capacitance. $Q$ and $n$ are represented constant phase element (CPE) and frequency power, respectively. The equivalent electrical circuit model with an inhibitor in figure 7(b) is added two parameters from figure 7(a). The two-parameter are $R_h$ and $C_2$. Both equivalent electrical circuit models as referring to figure 6 are offered to fit the EIS data by using ZSimpWin software [40, 42, 43].

The observed data from Nyquist plots are analysed by fitting with the equivalent electrical circuit model containing $R_s$, $R_{ct}$, $R_h$, $R_p$, $R_m$, $C_1$, $C_2$, $C_3$, CPE and $n$ as seen the fitting values in tables 5 and 6 for EIS data of stainless steel 304 welded pipe in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 7,500 and 15,000 cm$^3$ min$^{-1}$, respectively.
From the fitting results are tabulated in tables 5 and 6 show that \( R_h \) is increased when the inhibitor concentration is increased as same as \( R_m \). The \( R_m \) values are compared between with and without the inhibitor, the \( R_m \) value of the solution containing presence HEC inhibitor is strongly increased from that absence corrosion inhibitor. And the \( R_m \) value is increase when the HEC concentration is increasing. While observed \( R_p \) value does not change when increasing the concentration of inhibitors. The \( R_p \) is more increased when the flow rate is increased from 7,500 to 15,000 cm\(^3\) min\(^{-1}\).

### Table 5. Fitting results from equivalent electrical circuit corresponding to EIS data of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 7,500 cm\(^3\) min\(^{-1}\).

| Parameters          | 0 ppm   | 100 ppm | 300 ppm | 600 ppm |
|---------------------|---------|---------|---------|---------|
| \( R_s \) (\( \Omega \) cm\(^{-2}\)) | 306.000 | 300.400 | 294.300 | 276.900 |
| \( R_{ct} \) (\( \Omega \) cm\(^{-2}\)) | 1.022   | 264.700 | 268.000 | 261.400 |
| \( R_h \) (\( \Omega \) cm\(^{-2}\)) | —       | 2,413.000 | 3,017.000 | 4,091.000 |
| \( R_m \) (\( \Omega \) cm\(^{-2}\)) | 34,560.000 | 75,680.000 | 68,270.000 | 72,570.000 |
| \( R_m \) (\( \Omega \) cm\(^{-2}\)) | 2,417.000 | 65,960.000 | 78,070.000 | 79,160.000 |
| \( C_1 \) (\( \mu \)F cm\(^{-2}\)) | 0.482   | 0.473   | 0.315   | 0.144   |
| \( C_2 \) (\( \mu \)F cm\(^{-2}\)) | —       | 28.980  | 39.600  | 44.640  |
| \( C_3 \) (\( \mu \)F cm\(^{-2}\)) | 75.600  | 95.000  | 106.300 | 126.300 |
| CPE (\( \mu \)F cm\(^{-2}\)) | 61.190  | 32.080  | 235.900 | 86.240  |
| \( n \)         | 0.806   | 0.617   | 0.270   | 0.425   |
| \( \chi^2 \)     | 0.00227 | 0.01603 | 0.00605 | 0.0002519 |

From the fitting results are tabulated in tables 5 and 6 show that \( R_h \) is increased when the inhibitor concentration is increased as same as \( R_m \). The \( R_m \) values are compared between with and without the inhibitor, the \( R_m \) value of the solution containing presence HEC inhibitor is strongly increased from that absence corrosion inhibitor. And the \( R_m \) value is increase when the HEC concentration is increasing. While observed \( R_p \) value does not change when increasing the concentration of inhibitors. The \( R_p \) is more increased when the flow rate is increased from 7,500 to 15,000 cm\(^3\) min\(^{-1}\).

### 3.2. Potentiodynamic polarization measurements

The polarization curve of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 7,500 and 15,000 cm\(^3\) min\(^{-1}\) are shown in figures 8 and 9, respectively.
Table 6. Fitting results from equivalent electrical circuit corresponding to EIS data of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 15,000 cm$^3$ min$^{-1}$.

| Parameters | 0 ppm | 100 ppm | 300 ppm | 600 ppm |
|------------|-------|---------|---------|---------|
| $R_s$ (Ω cm$^{-2}$) | 305.900 | 304.600 | 303.900 | 297.600 |
| $R_t$ (Ω cm$^{-2}$) | 1003.000 | 315.300 | 301.000 | 296.700 |
| $R_h$ (Ω cm$^{-2}$) | 84,320.000 | 83,200.000 | 84,330.000 | 88,440.000 |
| $R_m$ (Ω cm$^{-2}$) | 2,938.000 | 75,880.000 | 96,300.000 | 159,600.000 |
| $C_1$ (μF cm$^{-2}$) | 0.387 | 0.304 | 0.291 | 0.221 |
| $C_2$ (μF cm$^{-2}$) | — | 28.473 | 32.140 | 30.200 |
| $C_3$ (μF cm$^{-2}$) | 71.600 | 73.860 | 132.080 | 123.100 |
| CPE (μF cm$^{-2}$) | 64.540 | 193.700 | 76.970 | 67.050 |
| $n$ | 0.817 | 0.302 | 0.409 | 0.453 |
| $\chi^2$ | 0.003618 | 0.01287 | 0.006737 | 0.002202 |

Figure 8. Polarization curve of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 7,500 cm$^3$ min$^{-1}$.

Figure 9. Polarization curve of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 15,000 cm$^3$ min$^{-1}$.
As refer to figures 8 and 9, the increasing of HEC inhibitor concentration is affected by the polarization curve of stainless steel 304 welded pipes in 3.5 wt% NaCl under flow rate 7,500 and 15,000 cm³ min⁻¹. If the HEC inhibitor concentration is increased, the corrosion potential ($E_{\text{corr}}$) is shifted down to more negative values.

Corrosion parameters are anodic Tafel slope ($\beta_a$), cathodic Tafel slope ($\beta_c$), corrosion potential ($E_{\text{corr}}$), current density ($i_{\text{corr}}$), polarization resistance ($R_{\text{po}}$) and corrosion rate ($CR$). Tables 7 and 8 are shown obtained results from the Tafel slope analysis technique by GPES software. The inhibitor efficiency (IE) percentages are calculated by using corrosion rate values and equation (1). And figures 10 and 11 are shown corrosion rate trends from analysis results by using the technique. The corrosion rate graphs are information for the relation of corrosion rate with HEC concentration and turbulent flow. The corrosion rate is decreasing if the inhibitor concentration is increased [44]. While the corrosion rate increases with increasing of turbulent flow [45–48].

**Table 7.** Corrosion parameters of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 7,500 cm³ min⁻¹.

| HEC inhibitor concentrations | 0 ppm | 100 ppm | 300 ppm | 600 ppm |
|-----------------------------|-------|---------|---------|---------|
| Parameters                  |       |         |         |         |
| $\beta_a$ (V dec⁻¹)         | 0.105 | 0.040   | 0.111   | 0.108   |
| $\beta_c$ (V dec⁻¹)         | 0.182 | 0.157   | 0.197   | -0.140  |
| $E_{\text{corr}}$ (V)       | -0.041| -0.129  | -0.056  | -0.140  |
| $i_{\text{corr}}$ (μA cm⁻²) | 4.708 | 3.967   | 2.528   | 1.602   |
| $R_{\text{po}}$ (Ohm)       | 702,000| 274,100 | 1504,000| 1532,000|
| CR (μm year⁻¹)              | 49.400| 41.630  | 26.530  | 16.820  |
| IE (%)                      | 0.000 | 15.729  | 46.296  | 65.951  |
| $\theta$                    | 0.000 | 0.157   | 0.463   | 0.660   |

**Table 8.** Corrosion parameters of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 15,000 cm³ min⁻¹.

| HEC inhibitor concentrations | 0 ppm | 100 ppm | 300 ppm | 600 ppm |
|-----------------------------|-------|---------|---------|---------|
| Parameters                  |       |         |         |         |
| $\beta_a$ (V dec⁻¹)         | 0.067 | 0.062   | 0.055   | 0.098   |
| $\beta_c$ (V dec⁻¹)         | 0.219 | 0.242   | 0.181   | 0.110   |
| $E_{\text{corr}}$ (V)       | 0.095 | 0.011   | -0.012  | -0.181  |
| $i_{\text{corr}}$ (μA cm⁻²) | 5.276 | 4.567   | 3.154   | 1.810   |
| $R_{\text{po}}$ (Ohm)       | 481,100| 576,700 | 548,300 | 1,036,000|
| CR (μm year⁻¹)              | 55.370| 47.720  | 33.100  | 19.000  |
| IE (%)                      | 0.000 | 13.816  | 40.220  | 65.685  |
| $\theta$                    | 0.000 | 0.138   | 0.402   | 0.657   |

**Figure 10.** Corrosion rate graphs of stainless steel 304 welded pipes in 3.5 wt% NaCl with 0, 100, 300 and 600 ppm HEC inhibitor concentrations under flow rate 7,500 cm³ min⁻¹.
3.3. Scanning electron microscope

Scanning electron microscope (SEM) is used to observe corrosion damage images of stainless steel 304 welded pipe in 3.5 wt% NaCl under turbulent flow, as seen in figure 12.

The pitting corrosion on the inner surface of stainless steel 304 welded pipe in 3.5 wt% NaCl under turbulent flow is observed at heat affected zone (HAZ). The HAZ is the area of microstructural changes in the stainless steel that is induced by heat input from welding currents or melting. Normally, the corrosion resistance of the welding area is inferior to more than base metals. Because of the inhomogeneous and dendritic microstructures are produced by heat input. The heat input leads to the detrimental phase such as chromium carbides that can be precipitated in the austenitic grain boundaries at HAZ [24, 49–51]. So the heat input process is a cause of the HAZ to the more sensitive area for the pitting corrosion than the area of base metal [7, 8, 52–54]. However, the corrosion can also be reduced violence by the heat treatment process [55–58]. As referring to the SEM image in figure 12(d), The morphology of stainless steel 304 welded pipe without inhibitor shows that is a rough surface from corrosion attack by sodium chloride solution.

From HEC’s molecular structure in figure 1, HEC is an organic inhibitor (adsorption inhibitor), so the inhibition mechanism can be clarified by the basic of adsorption phenomenon [18]. For the polarization curves between absence and presence inhibitors are in figures 7 and 8, $E_{corr}$ is shifted to negative value when increasing of the HEC concentration. Thus, HEC inhibitor can reduce reduction reaction by blocking the cathode reaction. The HEC inhibitor is adsorbed on the surface of passivation film (Cr$_2$O$_3$) as is supported by $R_h$ values. The $R_h$
values are a range of 2,400 to 4,100 \( \Omega \text{ cm}^{-2} \), which is not much value compared to \( R_p \) values in tables 5 and 6. The \( R_h \) values may be caused by the HEC inhibitor is adsorption on the passivation with the van der Waals forces or rough surface of the passivation film as same as an adsorbed film on the passivation film as seen in figure 13 [13, 59, 60]. The passive film on stainless steel may break down in the presence of chloride ions in the solution, and the breakdown site may stimulate localized corrosion such as pitting corrosion on the surface of the steel [61]. Then the HEC inhibitor interacts with the steel surface and renders protection of the surface from corrosion as referring to the \( R_{in} \) value in tables 5 and 6 [13]. The hydroxyl (OH\(^-\)) of HEC can attract each other electrostatically (via hydrogen bonds), causing the chains to build an ordered structure which is a barrier to the dissolution of the steel in the solution as seen the fitting results of EIS data in tables 5 and 6 to support the adsorption mechanism [18, 62, 63]. The relation between HEC inhibitor concentrations with the corrosion rates can be clarified by the \( \theta \) values as are shown in tables 7 and 8. The results of \( \theta \) values are increasing while the corrosion rate is decreasing with the enhancement in the inhibitor concentration. HEC inhibitor concentration is added to increasing inhibitor molecules in the solution. Then the molecules are transferred from the solution to adsorb on the metal surface. Therefore, the increasing amount of HEC inhibitor concentration is producing the inhibitors molecules to cover the metal surface and resulting in a reduced corrosion rate [21, 33, 34].

The flowing rate is related to the turbulent behaviour of the solution. And turbulence may affect to adsorption mechanism of the inhibitor by blowing the molecules of the inhibitors, that are adsorbed on surfaces of passivation and stainless steel. If the turbulent flow is increased, the inhibitor molecules may also come out from the surface more and affect the corrosion resistance of the inhibitor in the system [64, 65]. Besides, the convexity of the weld line may affect the turbulent flowing pattern and adsorption of inhibitor on the surface of stainless steel.

4. Conclusions

The virtual corrosion testing for stainless steel 304 welded pipes are used hydroxyethyl cellulose as a corrosion inhibitor in 3.5 wt% NaCl under turbulent flow. Electrochemical techniques are studied by using electrochemical impedance spectroscopy, potentiodynamic polarization measurements technique and SEM images. The principal conclusions are:

- The potentiodynamic polarization results are indicated that the HEC is an adsorb inhibitor.
- Enhanced corrosion resistance on the surface of stainless steel 304 welded pipe in 3.5 wt% NaCl solution is provided by HEC as is an eco-friendly inhibitor.
- The corrosion inhibition efficiency of HEC as in the condition is reached up to 66% by addition 600 ppm HEC concentration.
- Corrosion rate increases when the turbulent flow increases.
- Pitting corrosion can be observed on the HAZ of welding pipe by using SEM.
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