Numerical and Experimental Investigation of CO₂ Corrosion

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Abstract

Internal corrosion is a common problem in pipelines transporting oil and gas containing corrosive components such as CO₂ and H₂S. In many mature oil wells, the water cut and CO₂ content may reach high level which forms a suitable environment for initiation and growth of corrosion. To avoid the consequences of corrosion, process parameters should always be controlled within safe operating limits. To do so, corrosion rates at various values of the parameters are to be predicted to set the critical values of every parameter; and then the process should be operated below these critical values. Efforts have been made to predict and control corrosion in many oil fields worldwide. As a result, many models and measurement techniques have been proposed. One of these models is NORSOK Norwegian standard CO₂ prediction model (NORSOK 2005), which predict the corrosion rate due to presence of CO₂ in straight pipes that transport single phase or two-phase (oil-water) fluids. The model is a set of three equations for prediction of corrosion rate in straight pipe within temperature range of 5-150 °C. The effects of pH is introduced to the equations as a factor calculated at different temperatures and within different pH ranges using simple empirical
equations. The effect of CO₂ partial pressure is introduced to the model as CO₂ fugacity, which is calculated using a simple empirical equation.

In this paper, CO₂ corrosion rates at different conditions has been studied using NORSOK model after modifying it to adopt for elbows geometry. The results have then been validated against values measured from a flow loop using electrochemical noise measurement (ENM). The predicted corrosion rate fairly agreed with the measured values.

Introduction

Corrosion is defined as “the deterioration of a material, usually metal, by the reaction with its environment” (Jones, 1992). Internal and external corrosion is common in pipelines transporting oil and gas containing corrosive components such as CO₂ and H₂S. In many mature oil wells, the water cut may reach 90% and CO₂ may form 30% of the produced fluids. The presence of the brine with CO₂ forms a suitable environment for initiation and growth of corrosion.

To avoid the consequences of corrosion, process parameters should always be monitored and controlled within safe operating limits. To do so, accurate corrosion models are needed to estimate the corrosion rate and determine the critical values of the process parameters. The process then should be operated below these critical values.

Efforts have been made to predict and control corrosion in many oil fields worldwide. As a result, many models and measurement techniques have been proposed.

De Waard and Milliams (De Waard and Milliams, 1975) indicated that corrosion rate increases with CO₂ partial pressure and temperature until it reaches a maximum value at temperature 60-70 °C and then decreases until 90 °C. De Waard and his co-worker (De Waard, Lotz and Dugstad, 1995) proposed a semi-empirical model using data acquired from a high pressure test facility. Their model accounts for the contributions of kinetics of corrosion reaction and mass transfer of dissolved carbon dioxide. Their model, however, doesn’t account for the oil composition.

Jepson and his co-workers (Jepson et al, 1996) developed an empirical model for corrosion rate prediction in horizontal multiphase slug flow pipelines. Their model relates the corrosion rate to the pressure gradient across the mixing zone, water cut, temperature, and CO₂ partial pressure. The model has been improved in 1997 (Jepson et al, 1997) to account for the effect of slug frequency and oil type.

A mechanistic model for CO₂ corrosion in horizontal multiphase slug flow has been proposed in 2002 by Hongwei Wang and his co-workers (Wang et al, 2002). Their model covers the electrochemical reactions on steel surface, the chemistry of fluid, and mass transfer between the metal surface and the fluid.

Srđjan Nesic and co-workers (Nesic, 2005) developed a comprehensive model for internal corrosion prediction in mild steel pipelines. The effects of many factors affecting the corrosion rate such as H₂S, water entrainment in multiphase flow, corrosion inhibition by crude oil components and localized attack have been taken into account in the model.

In this paper, NORSOK model in straight pipes has been modified to make it applicable for elbows. This modified model can be combined with any erosion prediction model to predict the overall wear rate in elbows.

NORSOK standard CO₂ corrosion model (NORSOK, 2005) was developed by the Norwegian petroleum industry for calculation of corrosion rate due to the presence of CO₂ in hydrocarbon production and process systems.

NORSOK model

The model consists of three empirical equations calculating the corrosion rate in mm/year. Depending on temperature range, the three equations can be combined as follows (NORSOK, 2005):

2
To modify NORSOK model to be applied for elbows instead of straight pipes, a relationship to convert straight pipe wall shear stress into elbow wall shear stress has been developed. To this purpose the friction factor of straight pipe should be multiplied by the ratio of the equivalent length to the actual length of the elbow. i.e.: 

\[ f_{el} = f_p \frac{L_{eq}}{L_{act}} \]  

(4)

That means, the friction factor of straight pipe should be multiplied by the ratio of the equivalent length to the elbow actual length to convert it to the elbow friction factor.

ASME B16.9 was utilized to obtain the actual length of selected diameters of 45 deg long radius elbows and by using a relationship proposed by W. Trimmer and H. Hassan (Trimmer and Hassan, 1997), the wall shear stress of elbow is related to that of straight pipe as follows:

\[ S_{el} = 5f_p \rho V_m^2 \]  

(5)

And then, the modified NORSOK model for CO₂ corrosion in elbows can be written as follows:

\[ R_e = \begin{cases} 
  k_i \times f_{CO_2}^{0.62} \times \left( \frac{S}{19} \right)^{0.146 + 0.0324 \log(f_{CO_2})} \times f(pH), & T = 20^\circ C \leq T \leq 150^\circ C \\
  k_i \times f_{CO_2}^{0.36} \times \left( \frac{S}{19} \right)^{0.146 + 0.0324 \log(f_{CO_2})} \times f(pH), & T = 15^\circ C \\
  k_i \times f_{CO_2}^{0.62} \times f(pH), & T = 5^\circ C 
\end{cases} \]  

(6)

The extension of NORSOK model to elbows is discussed in details in Mysara E. Mohyaldinn (Mysara E. Mohyaldinn, 2011)

To calculate the friction factor, \( f \), the flow regime should first be identified according to the Reynolds number (Re), which can be calculated using the following formula:

\[ \text{Re} = \frac{\rho_m V_m D}{\mu_m} \]  

(7)
For laminar flow \((Re \leq 2100)\), friction factor is calculated using the formula:

\[
f = \frac{16}{Re}
\]  \( (8) \)

For turbulent flow \((Re > 2100)\), Churchil (Churchil, 1977) model is explicit in f and valid for both smooth and rough pipes. The model is written as follows:

\[
f = 2 \left[ \left( \frac{8}{Re} \right)^{12} + (A + B)^{-1.5} \right]^{1/12}
\]  \( (9) \)

Where

\[
A = \left[ 2.457 \ln \left( \frac{1}{C} \right) \right]^{16}, \quad B = \left( \frac{37530}{Re} \right)^{16}, \quad C = \left( \frac{7}{Re} \right)^{0.9} + 0.27 \frac{e}{D}
\]

e is the pipe roughness and \(D\) is the internal diameter.

**Results and discussion**

The original and modified NORSOK models have been implemented to visual basic programming to develop a computational package with friendly graphical user interface with an input data form shown in figure 1. The input data are those related to shear stress calculations and corrosion rate calculations.

![Figure 1: The input data form for corrosion prediction.](image)

**CO₂ corrosion prediction and simulation**

Employing the original and modified NORSOK CO₂ corrosion prediction models to the developed code (software) allows prediction of CO₂ corrosion in straight pipes or elbows under any conditions (input data). In this section we will present and analyze results of the code for CO₂ corrosion in an elbow and a straight pipe under arbitrary selected input data.
Table 1 shows the input data entered into the computational code for CO₂ corrosion prediction and simulation. The asterisk * indicates that the parameter can be set as variable, while other parameters are kept constant. That is to say, the corrosion rate variation with velocity, density, viscosity, and CO₂ partial pressure can be obtained as output in tables or graphical forms.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>20</td>
</tr>
<tr>
<td>CO₂ partial pressure (Bar)</td>
<td>0.2 *</td>
</tr>
<tr>
<td>pH</td>
<td>5</td>
</tr>
<tr>
<td>System total pressure (Bar)</td>
<td>10</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>0.075</td>
</tr>
<tr>
<td>Roughness (m)</td>
<td>0.0005</td>
</tr>
<tr>
<td>Fluid density (kg/m³)</td>
<td>1000 *</td>
</tr>
<tr>
<td>Fluid viscosity (Pa.s)</td>
<td>0.0015 *</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>5 *</td>
</tr>
</tbody>
</table>

**CO₂ corrosion prediction and simulation in laminar flow**

To investigate the contribution of the different flow parameters (Velocity, density, viscosity, and pipe diameter) on corrosion rate in laminar flow, the change of corrosion rate with respect to these parameters should be quantified. All these parameters implicitly affect the corrosion rate due to their direct relationship with shear stress. The shear stress, therefore, need to be substituted with these parameters. By substituting the Reynolds number (equation 7) into the friction factor for laminar flow (equation 8), the wall shear stress can be given as follows:

\[
S = \frac{16 \mu}{\rho V D} = \frac{8 \mu V}{2} \frac{D}{V}
\]  

(10)

From the above equation, in laminar flow, the shear stress (and so to the corrosion rate) is directly proportional to viscosity and velocity whereas it is inversely proportional to pipe diameter and not affected by the density.

We will consider the NORSOK equation which is applicable within 20°C ≤ T ≤ 150°C to obtain the effect of the three parameters on corrosion rate.

Let \( C_1 = K_1 \times f_{CO_2}^{0.62} \times f(pH) \), \( C_2 = 0.146 + 0.0324\log(f_{CO_2}) \), \( C_3 = \left[ \frac{0.42104 \mu}{D} \right]^{C_4} \), \( C_4 = \left[ \frac{0.421046V}{D} \right]^{C_5} \), \( C_5 = \left[ 0.42104 \mu V \right]^{C_1} \).

Then the first equation in the set of equations 1 (20°C ≤ T ≤ 150°C) can be written as follows:

\[
R_c = C_1 \left[ \frac{0.42104 \mu V}{D} \right]^{C_2} = C_1 C_3 V^{C_2} = C_1 C_4 \mu^{C_2} = C_1 C_5 \left( \frac{1}{D} \right)^{C_2}
\]  

(11)
And, the derivative of corrosion rate with respect to velocity, viscosity, and diameter can be obtained as follows:

\[
\frac{dCR}{dV} = C_1C_2C_3V^{C_4-1}
\]  
(12)

\[
\frac{dCR}{d\mu} = C_1C_2C_4\mu^{C_4-1}
\]  
(13)

\[
\frac{dCR}{dD} = -C_1C_2C_3D^{C_4-1}
\]  
(14)

The above equations indicate that corrosion rate increases with velocity and viscosity while it decreases with pipe diameter.

Considering the parameters in Table 1, the velocity below which flow regime is laminar can be calculated by substituting \( Re=2000 \) as follows:

\[
2000 = \frac{1000 \times V_c \times 0.075}{0.002}
\]

\[
V_c = \frac{2000 \times 0.002}{1000 \times 0.075} = 0.053 \text{ m/s}
\]

By introducing velocity values less than 0.05, we obtained the change of corrosion rate with velocity, density, viscosity, and diameter as in Figures 2 through 5. It is clear that corrosion rate increases with velocity and viscosity, decreases with pipe diameter, and remains constant when density changes, which agrees with the derivation above.

Figure 2: Variation of corrosion rate with velocity (laminar regime)
Figure 3: Variation of corrosion rate with density (laminar regime)

Figure 4: Variation of corrosion rate with viscosity (laminar regime)
Figure 5: Variation of corrosion rate with diameter (laminar regime)

CO₂ corrosion prediction and simulation in turbulent flow

In turbulent flow, the friction factor is calculated using the following equation:

\[
f = 2 \left( \frac{8}{\text{Re}} \right)^{12} + \left[ 2.457 \ln \left( \frac{1}{\left( \frac{7}{\text{Re}} \right)^{0.9} + 0.27 \frac{\varepsilon}{D}} \right) \right]^{16} + \left( \frac{37530}{\text{Re}} \right)^{16} \right]^{-1.5}^{-1/12} \tag{15}
\]

By substituting Reynolds number (equation 7), we obtain the friction factor as follows:

\[
f = 2 \left( \frac{8\mu}{\rho V D} \right)^{12} + \left[ 2.457 \ln \left( \frac{1}{\left( \frac{7\mu}{\rho V D} \right)^{0.9} + 0.27 \frac{e}{D}} \right) \right]^{16} + \left( \frac{37530\mu}{\rho V D} \right)^{16} \right]^{-1.5}^{-1/12} \tag{16}
\]

And the wall shear stress can be obtained as follows:
It is clear that the differentiation of the above equation is complicated. To quantify the effect of the flow parameters on shear stress (and hence on corrosion), we consider the term including the shear stress in NORSOK equation, giving it the name shear stress term (SST), as follows:

\[
S = \rho V^2 \left[ \left( \frac{8\mu}{\rho V D} \right)^{12} + \left[ 2.457 \ln \left( \frac{7\mu}{\rho V D} \right)^{0.9} + 0.27 \frac{e}{D} \right]^{16} + \left( \frac{37530\mu}{\rho V D} \right)^{16} \right]^{-1.5}^{1/12}
\]  

(17)

The shear stress term includes the flow parameters (velocity, viscosity, and density). The effects of velocity, viscosity, and density on SST in turbulent flow are given in Figure 6, Figure 7, and Figure 8 respectively. It is clear that the shear stress term (and so corrosion rate) markedly increases with velocity and insignificantly increases with density and viscosity.

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Figure 6: Variation of SST with velocity
The effect of flow velocity on CO$_2$ corrosion

In the NORSOK model, CO$_2$ corrosion is implicitly related to flow velocity due to its direct relationship with wall shear stress, which is proportionally related to the velocity raised to the power 2. Figure 9 shows how CO$_2$ corrosion rate (mm/year) changes with the flow velocity (m/s) for straight pipe and elbow with the same size using the input data shown in Table 1. It is clear that, corrosion rate markedly increases with velocity increase, and it is significantly higher in elbows than in straight pipe.
The effect of fluid density on CO$_2$ corrosion

The fluid density also affects the wall shear stress proportionally. The density increase leads to higher corrosion rate. Again, the increase of corrosion rate is mainly due to the effect of density on wall shear stress. The effect, however, is very slight compared to that of the velocity. Figure 10 shows the effect of fluid density variation on the corrosion rate using the input data shown in Table 1. Taking into consideration that oil density is, normally, in the range of 700 to 1000 kg/m$^3$, the effect of oil density on corrosion rate is negligible.

The effects of fluid viscosity on CO$_2$ corrosion

Corrosion rate has been found to increase as the fluid viscosity increases. A fluid with higher viscosity generates higher friction factor, which in turns induces higher shear stress. The effect, however, is too low to the extent that
it can be neglected; in particular for turbulent flow due to the fact that friction factor does not only depend on Reynolds number but also on roughness. The variation of corrosion rate with viscosity for turbulent flow is shown for straight pipes and elbows in Figure 11 using the input data shown in Table 1.

**Figure 11: The effect of fluid viscosity (Pa.s) on corrosion rate (mm/year)**

**The effects of CO₂ partial pressure on CO₂ corrosion**

The CO₂ partial pressure highly affects corrosion rate. The relationship is directly proportional. From NORSOK model, CO₂ partial pressure contributes to corrosion rate as CO₂ fugacity which is calculated using equation 2 and equation 3. CO₂ fugacity affects corrosion rate directly (raised to the power 0.62) and implicitly as a part of wall shear stress exponent. Figure 12 shows how the corrosion rate varies with the CO₂ partial pressure.

**Figure 12: The effect of CO₂ partial pressure (Bar) on corrosion rate (mm/year)**

**Effect of pH and temperature on corrosion rate**
The effect of pH on corrosion rate as given by NORSOK model is dependent on the temperature. The effect of pH on corrosion rate is calculated at different temperature using empirical models. Figure 13 and Figure 14 show that corrosion rate increases while pH decreases. Lower pH is indicator of higher acidity of the fluid. Temperature affects corrosion rate implicitly due to its direct relationship with $k_t$, an empirical constant tabulated in (NORSOK, 2005) and $f(pH)$ (the effect of pH). $k_t$ increases with temperature up to 60 °C to decrease after that up to 150 °C. In reality, temperature also affects the shear stress due to its effect on viscosity and, to a lesser degree, density. These effects, however, are not taken into account in this calculation. Figure 15 through 19 show that, in both laminar and turbulent flow, corrosion rate increases with temperature from 20 °C up to a maximum value between 60 °C and 80 °C to start declining after the maximum value. Anderzej Anderko and Robert D. Young (Anderko and Young 2001) obtained a similar result when calculating corrosion rate for carbon steel under a partial pressure of CO$_2$ equal to 30 bar. The maximum temperature they obtained, however, is between 80 °C and 100 °C. They explained that this maximum value results from the development of FeCO$_3$ surface layer which decelerate the attack of carbon steel by CO$_2$.

**Figure 14:** Variation of corrosion rate with flow velocity at different pH, T=60 °C

**Figure 15:** Variation of corrosion rate with pH, V=10 m/s, T=60 °C
Figure 16: Variation of corrosion rate with temperature at different velocity, $PCO_2=0.2$ bar, $pH=5$ (turbulent flow).

Figure 17: Variation of corrosion rate with temperature, $V=10$ m/s, $pH=5$ (turbulent flow)
Figure 18: Variation of corrosion rate with temperature at different velocity $\text{PCO}_2=0.2$ bar, pH=5 (laminar flow)

Figure 19: Variation of corrosion rate with temperature, $V=0.04$ m/s, $\text{PCO}_2=0.2$ bar, pH=5 (laminar flow)

Comparison of the model results with field data

The results of straight pipe corrosion rate predicted by the NORSOK model have been compared with field data taken from Gunaltun (Gunaltun 1991). The data used for the comparison are shown in Table 2. Nesic et al. (Nesic et al. 2005) used the same data to validate a corrosion model developed by them in 2005. Their validation result is shown in Figure 20. Using the field data shown in the table, the change of corrosion rate with flow velocity is shown in Figure 21. It is clear that the corrosion rate predicted by the model lays in the range between 2 to 3.5 mm/year whereas that predicted by the Nesic et al. (Nesic et al. 2005) model lays in the range between 1 to 4 mm/year, for the same range of velocity. We can say that the code gives acceptable agreement with the field data.
and Nesic et al. model. Figure 22 shows comparison between the predicted data from the code and selected data from Gunaltun field data (Gunaltun 1991). The comparison shows acceptable agreement.

Table 2: The field data of Gunaltun (Gunaltun 1991) (from Nesic et al. (Nesic et al. 2005))

<table>
<thead>
<tr>
<th></th>
<th>Umm Al Dalkh</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHFP (bars)</td>
<td>20 ~ 75</td>
</tr>
<tr>
<td>WHFT (°C)</td>
<td>30 ~ 70</td>
</tr>
<tr>
<td>BHFP (bars)</td>
<td>235 ~ 260</td>
</tr>
<tr>
<td>BHFT (°C)</td>
<td>100</td>
</tr>
<tr>
<td>Oil production rate (bopd)</td>
<td>65 ~ 2100</td>
</tr>
<tr>
<td>Water cut (%)</td>
<td>Up to 70</td>
</tr>
<tr>
<td>Oil density (at 20 °C)</td>
<td>0.872</td>
</tr>
<tr>
<td>CO2 content of the well fluid (mole %)</td>
<td>2.5</td>
</tr>
<tr>
<td>H2S content of the well fluid (mole %)</td>
<td>nil</td>
</tr>
<tr>
<td>GOR (SCF/SB)</td>
<td>70 ~ 200</td>
</tr>
<tr>
<td>Gas molar weight</td>
<td></td>
</tr>
<tr>
<td>Tubing size (inch)</td>
<td>2 3/8 ~ 3 1/2</td>
</tr>
<tr>
<td>Tubing material</td>
<td>C-75</td>
</tr>
<tr>
<td>Deviation (degree)</td>
<td>Up to 40</td>
</tr>
<tr>
<td>Water composition (mg/l)</td>
<td></td>
</tr>
<tr>
<td>Na⁺</td>
<td>59525</td>
</tr>
<tr>
<td>Ca⁺⁺</td>
<td>5890</td>
</tr>
<tr>
<td>Mg⁺⁺</td>
<td>755</td>
</tr>
<tr>
<td>K⁺</td>
<td>270</td>
</tr>
<tr>
<td>Fe⁺⁺</td>
<td></td>
</tr>
<tr>
<td>Ba⁺⁺</td>
<td></td>
</tr>
<tr>
<td>Sr⁺⁺</td>
<td>770</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>104425</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>410</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>260</td>
</tr>
<tr>
<td>pH (20 °C)</td>
<td>7.2</td>
</tr>
</tbody>
</table>
Figure 20: Comparison of Nesic et al. model results (Nesic et al. 2005) with Gunaltun field data (Gunaltun 1991)

Figure 21: Variation of corrosion rate with velocity using Gunaltun field data (Gunaltun 1991)
Another validation was carried on against data taken from (Wang et al. 2006) for a tubing transporting oil and water. The reported field data is in the range of 4.4 to 10 mm/year with no details about the tubing length and the corrosion rate at each point.

The predicted results in Table 3 are almost within the range of the reported field data.

Table 3: The tubing predicted corrosion rate

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>P (Bar)</th>
<th>PCO₂ (Bar)</th>
<th>Qt m³/d (V m/s)</th>
<th>D (m)</th>
<th>pH</th>
<th>WC (%)</th>
<th>CRp</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>270</td>
<td>1.56</td>
<td>800 (1.18)</td>
<td>0.1</td>
<td>5.05</td>
<td>5</td>
<td>5.42</td>
</tr>
<tr>
<td>80</td>
<td>250</td>
<td>1.56</td>
<td>1220 (1.8)</td>
<td>0.1</td>
<td>5.05</td>
<td>5</td>
<td>6.776</td>
</tr>
<tr>
<td>85</td>
<td>269</td>
<td>1.56</td>
<td>1220 (1.8)</td>
<td>0.1</td>
<td>5.1</td>
<td>47</td>
<td>3.775</td>
</tr>
</tbody>
</table>

Calculated value

Validation of the modified model

The modified model results have been compared with data measured using an erosion/corrosion flow loop. The flow loop consists of a screw pump circulating liquid from and back to a 300-L tank. CO₂ gas is injected from a cylinder connected to the loop before the test section (an elbow).

Methodology for corrosion measurement in elbows

CO₂ gas was injected from a cylinder connected to the flow loop before the test section. The electrochemical noise measurement (ENM) technique has been utilized for continuous online readings of potential and current fluctuations over time span. This technique allows corrosion rate monitoring without disturbances of the flow process. The monitoring of corrosion rate using ENM can be done by converting the potential/current fluctuations into useful information of corrosion rate and type using different methods. Aballe et al. (Aballe, Bethencourt et al. 1999) proposed three methods for interpreting ENM signals into quantitative and qualitative corrosion rate information. These methods are statistical methods, spectral analysis, and the chaos theory-based method.
GillAC potentiostat has been used to record and analyze the electrochemical noise measurements collected from a 3-in mild steel elbow. The corrosion rate measurement procedure is shown in the following chart:

![Figure 23: Corrosion Experimental Procedure](image)

**Corrosion rate measurements**

Corrosion rate was measured by connecting the electrodes to their corresponding wires in GillAC potentiostat, which was connected to a computer. The potentiostat signals were displayed in the form of simultaneous fluctuations of current and potential with time. A software package called sequencer was used to display the signals and to analyze the results to obtain the corrosion rate in mm/year. Figure 24 indicates that the predicted values agree fairly with the measured values. The measured values are 15 points for corrosion rate measured at five flow velocities and three values of pH.

![Figure 24: Measured and predicted corrosion rate](image)
Conclusion

NORSOK standard CO₂ corrosion prediction model has been modified to make it applicable to elbows in addition to straight pipes. A visual basic computational package with friendly graphical user interface has been developed to implement the original and the extended NORSOK models. The results of the program show significant increase of the corrosion rate in elbows in comparison with that in straight pipe. The program allows the investigation of the effect of different model parameters on corrosion rate. The following effects were found:

1. In laminar flow, corrosion rate increases with the increase in fluid viscosity and velocity and decreases with the increase of pipe diameter.
2. In turbulent flow it is mainly affected by velocity. It is increases with the increase of velocity. The corrosion rate increases with the increase of viscosity and density to a lesser degree.
3. Corrosion rate increases with the increase of CO₂ partial pressure which is directly related to the ppm of CO₂ dissolved in the fluid.

References