The Simulation and Analysis of Erosion Corrosion of CO_2 Pipelines - A Review

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Abstract: Oil and gas production activities use pipeline to distribute raw materials of oil from reservoir to the other processing facilities. These raw materials of oil/crude oils composes elements such as CO_2 gas and solid particles which are potential to damage pipe wall through erosion corrosion reactions. Unpredicted design gives fatal impact to the operational process and interrupt continuity of oil distributions. Therefore, it needs corrosion prediction to manage integrity strategies in oil companies. Considering multiple effects created by various corrosive factors, fundamental knowledge to understand corrosion mechanism is important to study in designing corrosion prediction software. To date, numerous corrosion predictions models with different approaches have been developed by oil and gas companies. This paper reviews the applications of fundamental theories of corrosion used by software (ECE, Norsok, Freecorp) in calculating erosion corrosion rate of carbon steel pipes. The concept of existing corrosion software is discussed. Parameters used and range of conditions are also studied. From the results of studies, it can be notified that corrosion predictions software have a prospective tool for determining degradation rate of carbon steel pipes in future. They also have benefits in selecting materials for pipelines and predicting service life of the pipes accurately.

Keywords: erosion corrosion, corrosion model, flow rate, carbon steel pipelines.

1. Introduction

Oil productions involve the pipelines to transport much volumes of oil from the oil reservoir to the other facilities for processing. The composition of oil varies depending on the location, age of the oil field and also the depth of the well. Raw of oil comprises mixed with chemical in the form of liquid, solid and gas phases (Zaini et al., 2014; Wei sun et al., 2006; Videm., 1994; Pawel et al., 2018). The mixtures are dangerous if the liquid carries chemical such as CO_2, H_2S mercury and Cl, HF, naphtanic, acetic or solids (sand) (Martin et al., 2009; Asmara et al., 2014, Norasma et al., 2011). Corrosion can cause localized damages in metals surfaces (Silverman et al., 1988). Corrosion can be accelerated when the cracks present (Asmara et al., 2013). In oil and gas environments, the dominant elements causing corrosion are CO_2 gas and H_2S gas (Michail et al., 2002; Sutjipti., 2017; Asmara et al., 2011). Corrosion caused by CO_2 and H_2S gases are called acid corrosion and sour corrosion, respectively (Asmara et al., 2015). The presence of solid particles and corrosion products affect erosion in pipe materials (Asmara et al., 2016). Mechanical effects due to water motion which causes impingement leads to metal removal and material abrasion (Eisenberg et al., 1954). Combination between mechanical and electrochemical effects impact on metallic integrity. This complexity of CO_2 corrosion is crucial aspect in constructing CO_2 corrosion model efficiently (Martin et al., 2009; Asmara et al., 2014). Current challenges of existing models are optimizing simultaneous interaction among variables to achieve accurate results in predicting corrosion process.

1.2.Flow-Induced Corrosion

Flow-induced corrosion is a type of corrosion caused by a combination of mechanical and electrochemical effects. Mechanical effects due to water motion causes impingement that leads to metal removal and material abrasion. Water that flows to the surface can wear the corrosion product film or create shear stress to the surface. Thus, corrosion will occur faster (Eisenberg., 1954; Silverman, 1988). Corrosion rate also can increase due to effects of differences in velocity turbulence across the surface. Parallel flow can also reduce thickness of the boundary layer, thus allowing active species to reach the metal surface quickly. Parameters that influence flow induced corrosion are hydrodynamic boundary layer and rate of momentum transfer from the bulk to the wall. In this conditiion, corrosion may be controlled by the rate of mass transfer of a reactant or the rate of corrosion products (William et al., 1975)

2. The uses of rotating cylinder electrode to simulate flow induced corrosion Rotating Cylinder

Electrode (RCE) has been used widely to simulate flow happening in the pipeline (Silverman, 1988). RCE is an alternative corrosion test that can be used to simplify flow induced corrosion phenomena from flow loop system. By using the disk rotating rate on RCE, fluid flow effects on corrosion can be simulated in the laboratory and it is possible to control the hydrodynamic conditions that occurs on the surface of the metal sample.

2.1 Turbulent and mass transport in RCE experiments

At high rotation flow, the solution flow will have complex mechanism creating several model flows. The shear stress on the sample surface becomes significant to form turbulent flow. The transition from laminar flow to turbulent flow can be related to Reynold's number. This condition can be a factor that governs corrosion behavior as an effect of oxygen transport. Corrosion reaction occurs at the solution through diffusion mechanism. Thus the current can be limited by rate of diffusion reactions. For the maximum of concentration gradient, the diffusion limited current density can be written as (Silverman, 1988):

$$i_L = -FD\left(\frac{c_{bulk} - c_{x=0}}{\delta}\right) \tag{1}$$

Where: i_L is limiting current for anodic reaction, C_{bulk} is bulk concentration of cathodic current, δ is diffusion layer thickness, D is coefficient of diffusion and F is Faraday's constant.

As reported by Eisenberg (Eisenberg, 1954) the most commonly accepted description for RCE mass transport, particularly, the mass transfer coefficient, *Km* (cms^{-1}) to a rotating cylinder is given by the following relationship:

$$K_m = (D/d_{cyl})\,\mathrm{Sh} = (D/d_{cyl})\,(0.0791\ \mathrm{Re}^{0.7}\ \mathrm{Sc}^{0.356}) \quad (2)$$

Where the diffusivity, D ($cm^2 s^{-1}$), is usually taken as the diffusion coefficient for the molecule or ion undergoing mass transport, and Sh and Re are the dimensionless Sherwood's and Reynold's numbers, respectively.

3. Wall shear stress for RCE

Shear stress is a stress, which is either parallel or tangential to the surface of a material. The physical quantity of shear stress is measured in force divided by area. In fluid flow, fluid moving along a surface will cause a shear stress on that surface. The shear stress can be expressed as (Silverman, 1988):

$$\tau_W = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0} \quad (3)$$

Where μ is the dynamic viscosity of the fluid, u is the velocity of the fluid along the boundary and y is the height of the boundary.

The turbulent flow at the RCE induces a wall shear stress on the surface of the cylinder. Again, Eisenberg reported a well-accepted equation for the wall stress, $\boldsymbol{\tau}_{cyl}$ ($g\ cm^{-1}\ s^{-2}$):

$$\boldsymbol{\tau}_{cyl} = 0.0791\ \rho\ \mathrm{Re}^{-0.3}\ U_{cyl}^2 \quad (4)$$

Where $\boldsymbol{\tau}_{cyl}$ is wall stress, ρ is density, Re is Reynold's number and U_{cyl} is velocity.

3.1 Accuracy of RCE

Figure 1. presents effect of rotation speed on corrosion rate studied using RCE. Data from RCE is compared with data calculated using software. As can be seen from the Figure 1, there are confirmed that increasing flow rate caused increasing corrosion rate. However, RCE data calculated corrosion rate higher than Freecorp software (14). RCE states that increasing flow, corrosion rate continues increase, while freecorp finds that the highest corrosion rate occurs at 1000 rotation speed. Freecorp (14) indicates that when rotation speeds are more than 1000 rpm, corrosion rate will remain constant. Freecorp was included limiting current density in calculating corrosion rate which make corrosion rate remain constant.

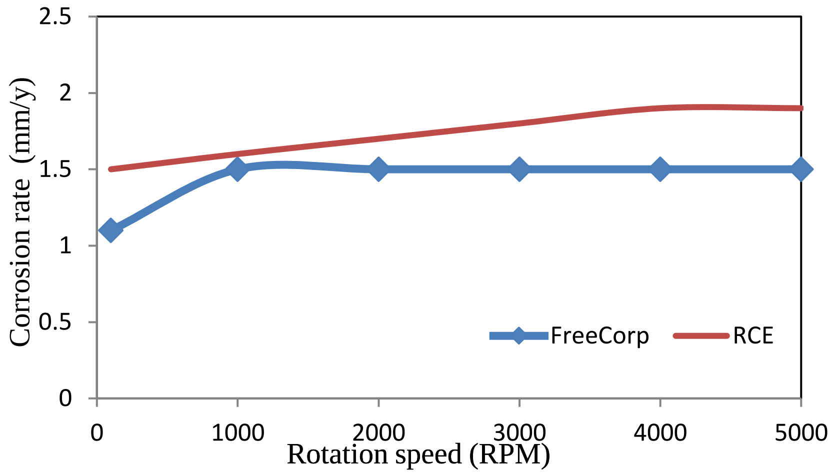

Figure 1. Effects of flow on corrosion rate as conducted with ECE experiments and calculated by FreeCorp software prediction.

4. Corrosion software in predicting erosion corrosion of CO_2 pipelines

4.1 Norsok

Norsok is manufactured by the Norwegian Oil Industry Association and Federation of Norwegian Manufacturing Industries. This corrosion calculation program calculates the corrosion rate based on the input CO_2 as the dominant contaminant, and does not specifically calculate the effects of O_2 and H_2S. This model is calculated empirically by involving parameters: temperature, shear stress, CO_2 fugacity, pH, wall shear stresses, and temperatures from 20 to160°C. The model calculates pH and wall shear stress. The effect of acetic acid is not account for in this model, but it is still valid to predict corrosion rate if the concentration of acetic acid is less than 100 ppm.

$$CR_t = K_t x f CO_2{}^{0.62} x (S/19)^{0.146+0.0324\log(fCO_2)} \\ x f(pH)t \tag{5}$$

Where CR is the corrosion rate (mm/yr), K_t is the constant for the temperature t, f CO_2 is the fugacity of the CO_2 (bar), S is Wall shear stress (Pa), $f(pH)t$ is the pH factor at temperature.

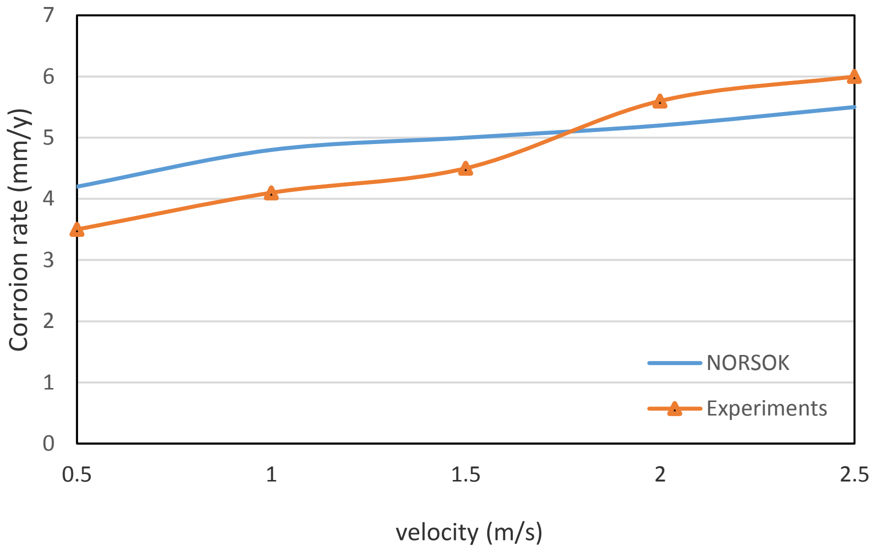

Figure 2. Comparison erosion corrosion as calculated using Norsok and experiments.

4.2 FreeCorp model

Freecorp applies electrochemical corrosion reactions in calculating corrosion rate. The model study oil flow in a steady state and transient condition based on bulk water chemistry. It include the formation of any kind of surface corrosion product layers. The two main elements cover in electrochemical corrosion of mild steel due to aqueous CO_2 and H_2S. The software consider additional homogeneous reactions of species of organic acids such as formic acid (HCOOH) and propionic acid (CH_3CH_2COOH) and acetic acid (CH_3COOH). Validation of freecorp using data experiments showed a good agreement and satisfy in interpretation corrosion behavior. Data experiments using polarization and Tafel test was conducted in dynamics condition.

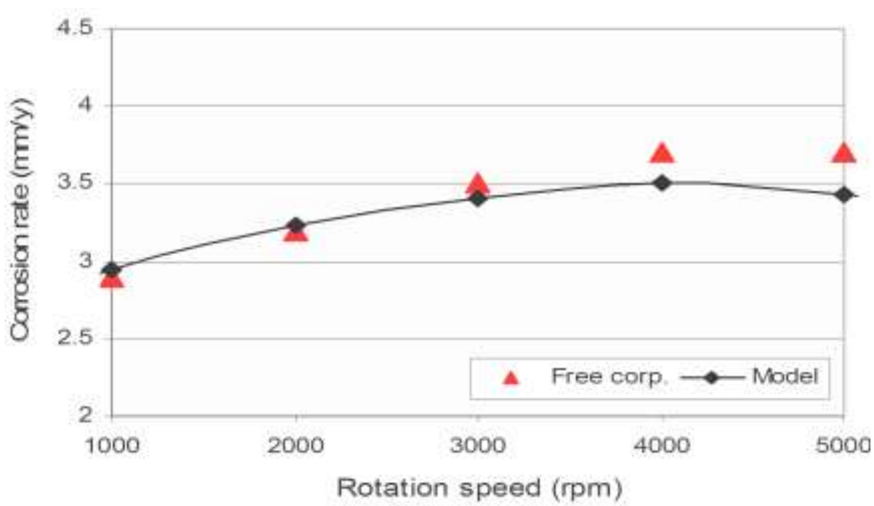

Figure 3. Comparison between the experimental model and Freecorp (CO_2 solutions at 35°C, 1 bar).

The effects of flow rate on corrosion rate of carbon steel in 2% mol CO_2 and 10% H_2S at pH 4 and temperature 40°C are presented in Figure 3. The data were calculated using Norsok and Freecorp software. From Figure 3, both calculations show an increase in corrosion rate with the increase of rotation speed. Both data predict that corrosion erosion continuously increase with increasing flow rate of water. This trend is similar to the corrosion rate happened until 8 m/s of flow rate.

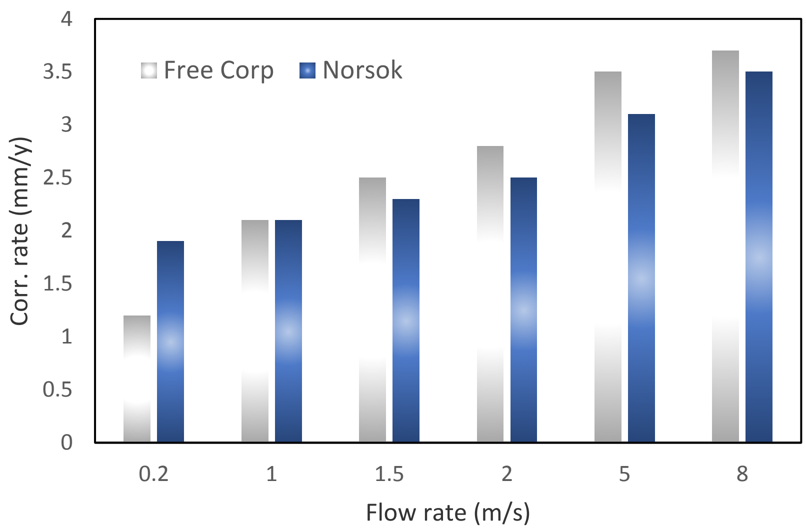

Figure 4. Comparison of effects of flow rate on corrosion rate calculated by Norsok and Freecorp.

4.3 Electronic Corrosion Engineering (ECE)

Electronic Corrosion Engineering (ECE) Method The ECE program is a model for predicting internal corrosion that occurs in carbon steel pipes. The resulting corrosion model explains the corrosion behavior due to the presence of water contained in CO_2 gas, H_2S gas, acetic acid and bicarbonate salt. ECE proposes a corrosion prediction expression using corrosion reactions and mass transfer effects. The mass transfer represents the main part of the dependence on flow velocity and pipe diameter. In ECE, they develop corrosion prediction by involving several variables such as gas fugacity, formation of protective films, effect of ferrous ions, presence of oil, effect of condensing water, and effect of multiple phase. They proposed a corrosion prediction expression as :

$$V_{cor} = \frac{1}{\frac{1}{V_r} + \frac{1}{V_m}} \qquad (6)$$

Where, V_r is corrosion reaction and V_m is mass transfer effect

5 Eelctrochemical model

Based on electrochemical theories, in solution contains CO_2 gas, mechanism of CO_2 corrosion involves anodic dissolution of iron and the cathodic reduction of undissociated carbonic acid. However, when any other species (HAc) is present, those species will influence corrosion and affects the corrosion mechanisms. The model combines between thermodynamics and electrochemical process.

Anodic Reactions

In anodic reactions, there is dissolution of metal. The mechanism is activation control. Anodic charge transfer in carbon steel is expressed as (Asmara et al., 2011):

$$i_{(Fe)} = i^{o}_{Fe} \exp\left[\frac{-\alpha_{Fe} F\left(E - E^{o}_{Fe}\right)}{RT}\right] \tag{7}$$

$$i^{o}_{Fe} = i^{*}_{Fe} a_{OH} a^{1.6}_{H_2O} \tag{8}$$

Cathodic Reactions

In acidic solutions, the reduction of H^+ is the dominant cathodic reaction. There are two possibilities reactions in cathodic sites (Wei sun, 2006). Which are diffusion limiting current density and activation current density. Activations current density are given by expression (Wei sun, 2006):

$$i_{H,a} = i^{o}_{H} \exp\left[\frac{-\alpha_{H} F\left(E - E^{o}_{H}\right)}{RT}\right] \tag{9}$$

The exchange current density is given by

$$i^{o}_{H} = i^{*}_{H} a^{0.5}_{H} a^{2.2}_{H2O} \tag{10}$$

Where a_H is activation of hydrogen ions and a_{H2O} is activation of H_2O.

The limiting current density results from diffusion-limited transport of protons to the metal surface and can be calculated as

$$i_{H,\lim} = K_m F a_H \tag{11}$$

where *km* is the mass transfer coefficient. The value of *km can* be calculated if the flow regime, diffusion coefficient of H^+ ions and solution viscosity are known.

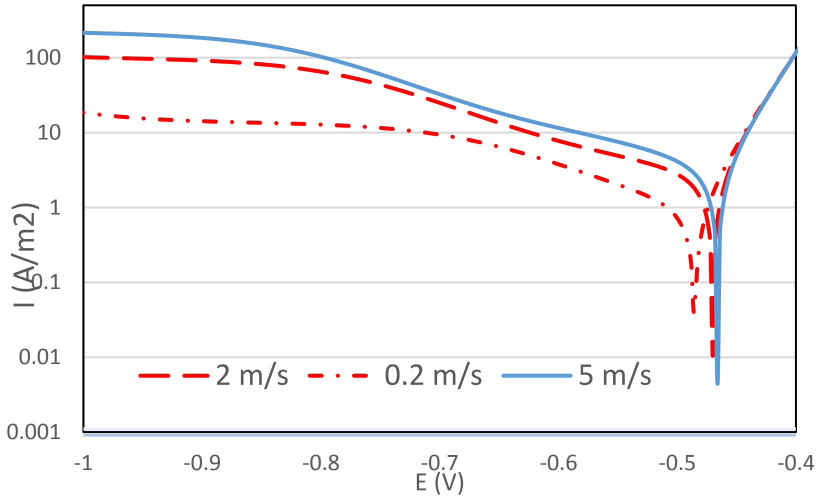

Figure 5. Effects of water flow rate at condition: 1 bar, 2 % CO_2, 10% H_2S, pH 4, 40^{o}C. as calculated based on electrochemical theories.

6 Second- order model regression in predicting erosion corrosion

Corrosion process can be constructed mathematically from mechanistic theory by using fundamental concepts of electro chemical reactions. The best mathematical formulas for describing corrosion process are Second- order model regression. There is a curvature of general second order model which is expressed as (Asmara et al., 2017):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j} \sum \beta_{ij} X_i X_j + \varepsilon \tag{12}$$

$\hat{Y} =$ predicted value (independence factors)

Where Y = response that can fit the following linear, quadratic, or cubic regression models, β = regression constant, *X* = main effect of dependence factors, and *XX* = interaction effects between dependence factors. Figure 5 and Figure 6 show validation of second degree regression with data from experiments at pH5 and pH 6 respectively. Both showed a good agreement and satisfy in interpretation erosion corrosion process.

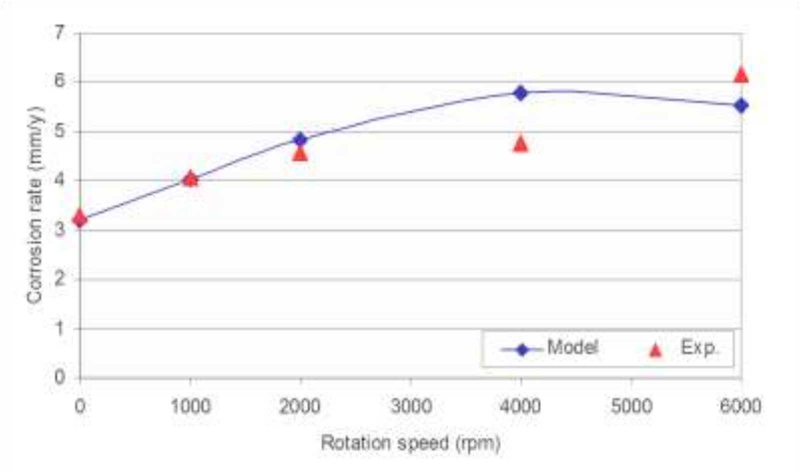

Figure 6. Effect of rotation speed on corrosion rate; a comparison between model and Martin's experiments (saturated CO_2 solutions, 60^oC, 20 ppm HAc, and pH 5).

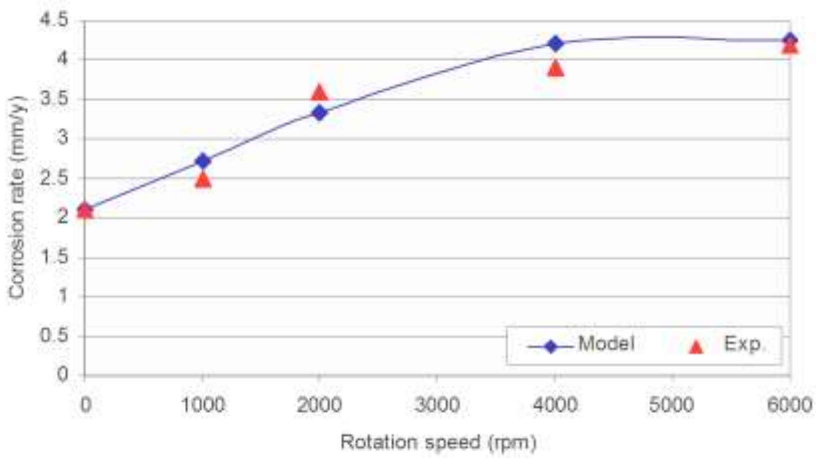

Figure 7. Effect of rotation speed on corrosion rate; a comparison between model and Martin's experiments (saturated CO_2 solutions, 40 ppm HAc, pH 6, and Temperature 60^oC).

7 Erosion corrosion simulation of bend pipes

CFD software is used to predict the maximum erosion rate in three types of elbows (Asmara et al., 2016). Table 1 shows CFD simulation calculation of corrosion erosion at 45^o, 90^o and 180^o elbow at 0.5 m/s. Based on the table, the highest corrosion erosion happened at 45^{o}c pipeline elbow. From investigation using CFD, it is caused by significantly increase of shear stress at 45^o compared 90^o and 180^o. In the other words, corrosion erosion is dominated by impact of shear stress. Investigating critical location, it shown that highest corrosion erosion was occurred at the wall that facing toward the fluid inlet which shows that synergy of erosion and corrosion is occurred simultaneously. Therefore, the erosion area is more critical when corrosion is initiated while the surface has start eroded. The combined effects of erosion and corrosion have shown a significant in increasing corrosion process. This synergism effects, as proposed by many researchers (Wei sun et al., 2006), was due to erosion and/or corrosion which occurs simultaneously. It was accepted that effect of flowing solid particles causes impingement to the protective layer on the metal surface which resulting exposure of metal surface. The more exposed metal surface area, the more corrosive environment in contact with metal to enhance corrosion rates.

Table 1. Comparison between Simulation resul (Asmara et al., 2016)

Elbow types	Velocity (m/s)	Maximum corrosion erosion rate (mm/year)	
	0.5	CFD result	Experimental result
45^{o}		1.9	2.3
90^{o}		1.5	1.1
180^{o}		1.6	1.9

Theoretical result* of maximum erosion rate at 45^{o} pipeline elbow with several fluid velocities as compared with experimental works [8].

Conclusion

In general, all models confirm that there is synergism effect between corrosion and erosion. The corrosion process is accelerated by erosion process. The erosion comes from liquid motion which impinge metal. The presence of aggressive elements causes faster corrosion reaction. In general, the use of software will help to estimate erosion corrosion. The models are able to simulate erosion corrosion process efficiently. It shows a good relationship among the variables known. Using software, the effects of variables will be easier to identify accurately. Mathematical operations are able to solve complex interactions among variables. In CO_2 corrosion, polynomial models are the most widely accepted and provide best fit regression. The appropriateness of the models have proven to estimate CO_2 erosion corrosion accurately. Thus, using predictive models, empirical studies can be minimized. Predictive model has a potent tool to investigate effects of CO_2 corrosion in several unknown variables.

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