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Mathematical Modeling and Simulation of Corrosion Processes in Nigerian Crude Oil Pipelines

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In this work, a corrosion prediction mathematical model for risk assessment in oil and gas production and transportation facilities has been created. This work focuses on partial pressure of carbon (iv) oxide, CO_2 and the operating temperature in process equipment and transportation facility pipes as a function of corrosion rate. The model equation formulated was based on the principle of multiple linear regressions of data. The final model representing the corrosion rate of crude oil equipment was obtained $CR = b_o + b_1 T + b_2\, P\,(CO_2)$. The model was simulated using polymath software. The correlation between the experimental and simulated resulted obtained using root mean square deviation (coefficient of determination) was 99.74% which is high, suggesting that the relationship between the predictor and response variables is linear. The variation in the model equation is 0.0066374. This low value of the variance shows that the model is accurate.

Keywords Corrosion rate, crude oil pipelines, risk assessment, simulation modeling

INTRODUCTION

In oil production plants, many cases of extensive corrosion have occurred in production tubing, valves, and in flow lines from the wellhead to the processing equipment. The reason for this is that oil and gas from the well contain varying amount of water, which can be precipitated as a separate phase in contact with the material surface, and that this water contains gases such as CO_2 and possibly H_2S, as well as salts. In most cases of severe corrosion, CO_2 plays a major role. In oil refineries, various corrosion problems exist, usually due to inorganic species, such as H_2S, CO_2, H_2SO_4, and $NaCl \cdot CO_2$ corrosion is called "sweet" corrosion.[1] Carbon (IV) oxide (CO_2) corrosion represents the greatest risk to the integrity of carbon steel equipments in a production environment and transportation facilities of oil and gas industries. Compared with the incidences of fatigue, erosion, stress, corrosion, cracking or over pressurization, the incidences of CO_2 related damage are far more common.[1]

In the mechanism of the main cathodic reaction in CO_2 corrosion the carbonic acid reacts with steel, and a layer of reaction products, to a large extent $FeCO_3$, is formed on the steel surface. The deposit is cathodic relative to steel, and when small defects occur in the deposit layer, pitting corrosion is developed. The conditions may be particularly corrosive in the production tubing, which carries the oil/gas up from the well. In production tubing of carbon steel, corrosion rates in excess of 10 mm/year may occur under unfavourable conditions. Various factors contribute to the high corrosivity: water content, salt content, high total pressure, considerable concentration (%) of CO_2 in the gas, high temperature and high flow rate.[1]

In pipe systems on the platform, the most severe corrosion attacks have been found between the wellhead and the first-stage separator, where water is precipitated, and where pressure, temperature as well as flow velocity are highest.[1]

Water is separated from oil and gas in separators ("produced water system"). In cases with high water content, it has corroded much more than expected. Penetration of the material after a few years of service has been reported.[1]

This has happened because the fluid goes from high to low pressure; the water is therefore supersaturated with CO_2 while it is in the produced water system (the "seltzer effect"). Consequently, when the water content is high the design should be based upon the conditions in the high-pressure system. When the water content is low, the time for the water to be present in the low-pressure system is much longer; equilibrium is reached and the mentioned problem is avoided. The corrosion rate may increase because of small amounts of oxygen in the water. Inhibitors added at the wellhead are not efficient in the "produced water system."[1]

Metallic corrosion is the passage of the metal into the chemically combined state. There is no mystery about

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corrosion. It is a natural phenomenon which proceeds according to well-understood laws. The corrosion of iron or steel (rusting), for example, completes the natural cycle begun when man extracts the metal from the ore. The actual measures to avoid unacceptable rate of CO_2 corrosion in general are to use inhibitors and/or stainless steels, and possibly coatings. The use of inhibitors may be expensive, and stainless steels become more and more common.[1]

Unfortunately, the engineering solutions to eradicating the CO_2 corrosion risk require high capital investment in corrosion resistant materials. Providing a corrosion allowance of 8 mm to carbon steel flow lines cost a significant sum at #116,000,000 per 5 km but even this is insignificant in terms of the cost of the various corrosion resistant flow line options.[2]

Similar relative costs are incurred when specifying corrosion resistant materials down hole or in facilities. This is rarely justified. For this reason, CO_2 corrosion of carbon steel will always be a problem that oil and gas industries has to deal with. Managing CO_2 corrosion therefore becomes a priority and it can become expensive. The replacement of the original MOL pipeline in Scarfa, Canada and the severe damage to the Beatrice MOL are two examples of high costs that oil and gas industries have incurred in recent years due to unpredicted corrosion rates. Successful management of CO_2 corrosion starts off with the identification of risk and continues with the provision of suitable controls and the review of the success of the controls via monitoring.[3]

The quantification of corrosion risk is required at several stages during an assets life. The most obvious period is during the project phase when the original materials of construction are being selected. This process must be repeated during the life of the assets if failures of expansions require the procurement of additional facilities. Quantifying the corrosion risk is also important in tailoring inspection strategies. Risk based inspection is now widely adopted and as CO_2 corrosion represents one of the most important factors governing the probability of failure for much equipment, a reasoned approach should be taken. It is important that this approach is theoretically sound but also reflects past experience.

This research sought the development of model to the quantification of CO_2 corrosion risk through the use of predictive models. In doing so, it also discusses the reliance that can be placed on corrosion inhibition as the only viable control measure for carbon steel and the importance of suitable corrosion monitoring. To put the importance of this into context, corrosion in oil and gas industries cost 8.3% of its capex budget and increases lifting costs by 14%, an average of over 8 cents per barrel.[2] It also considers the probabilistic approach to predicting CO_2 corrosion. Probabilistic approach to design in general is becoming more widespread and offers several advantages over the traditional deterministic approach. The corrosion model should be able to predict the effects of changing flow velocities on uninhibited corrosion rates. The approach to designing for the use of corrosion inhibitor has been changed significantly. The previous approach described the effects of an inhibitor through the use of efficiency factor, such as 90%. This does not reflect petroleum industries recent field data generated under severe conditions which showed inhibitors can be more effective than predicted. "Inhibitor efficiencies" have therefore been replaced with "inhibitor availabilities" that more closely reflect field experience. There is a general move in the industry towards this methodology and it offers several advantages.[4] However, it has become clear that for inhibitors to do work effectively that corrosion management system must be highly organized. Recommendations are therefore included on methods to ensure that the inhibitor availabilities assumed at the design stage occur during the operational stage.

The objective of this project is: (1) to develop a corrosion prediction models for risk assessment in oil and gas production and transportation facilities; (2) to development a model to the quantification of CO_2 corrosion risk through the use of predictive models; and (3) to development CO_2 corrosion prediction model for risk assessment in oil and gas production and transportation facilities obtaining CO_2 corrosion data from oil and gas industry Simulation of the model developed in step 1. Comparing simulated results obtained in step 3 to that of step 2. Discussing the deviation of the results compared in step 4 using statistical correlation.

Mathematical Modeling and Simulation

At the chemical laboratory of the Kaduna Refining and Petrochemical Company (KRPC), weight loss corrosion tests were performed on crude oil transportation pipes exposed in autoclaves simulating average conditions of well heads (4 bar CO_2 and 30°C). Water cuts were higher than 20% in all cases, and total volume inside the autoclave was always kept at 1.5 L. Test sequence was 20, 50, 80, and 99% of water (v/v), except on the cases of very heavy crude oils (CDU II crude) that could only be tested at 80 and 99% water. A rotating speed of 500 rpm was kept in order to get a homogeneous mixture of crude oil and water solution.

Process equipment metals and crude oil transportation pipes were the steels selected for this study but no significant differences were found between the two types of steel, and only and only crude oil transportation pipe results are shown in this project. Two coupons were used for each set of testing conditions; the two coupons were used for corrosion rate calculations. Coupons were grinded using a silicon carbide sand paper of grids 600, then cleaned with acetone, distilled water and dried. Their dimensions were taken and their weight determined using an analytical balance. The coupons were accommodated in the autoclave using a Teflon holder, the solution was poured and the autoclave was then closed and introduced in the heater assembly. The autoclave was purged with CO_2 for 30 minutes, to remove the air that could be inside. After deaeration, the equipment was pressurized until a pressure of 4 bars CO_2 was reached and maintained, and then temperature was raised until 30°C in 1-hour time period. Once the conditions were found, the test was performed with a total time of 120 hours.

Descaling of the coupons for the calculation of corrosion rates was made according to the standard ASTM G1–90. The same procedure were repeated for temperatures of 32°C, 34°C, 36°C, 37°C, and corresponding partial CO_2 pressure of 5 bar, 6 bar, 7 bar, and 8 bar.

The main purpose of developing this model is to be able to predict the following process parameters. The partial pressure of CO_2 in process equipment and transportation facilities pipe as a function of corrosion rate. The partial pressure of operating temperature in process equipment and transportation facilities pipe as a function of corrosion rate

Model Assumptions

Model assumptions for multiple regressions are likewise similar to those for simple linear regression. The effect of free water is tolerated and regarded to be of negligible risk for corrosion under these circumstances. The temperature of the line does not drop below the water dew point. The operating temperature is kept below 70°C to neglect effect of corrosion product scales. The effect of corrosion under condensing condition was neglected. Corrosion inhibitors were not injected into the system.

Multiple Linear Regression Model of Corrosion Rate in Oil and Gas Transportation System

The model for a multiple regression of the data obtained above is simply an extension of the simple linear model. The difference lies in the number of independent variables:

$$Y_i = \beta_0 + \beta_1 \cdot X1_i + \beta_2 \cdot X2_i + \varepsilon_i \quad [1]$$

Although it is difficult to imagine in more than two dimensions, the value of β_0 represents the intercept of the true population regression surface. Each β_k ($k = 1, 2, \ldots, p$) represents the slope of the surface with respect to Xk (specific gravity, rundown rate and temperature).

Response Surface

In a simple linear regression, taking the expected value of the experimental regression equation gives the true experimental regression line,

$$yf(x) = \beta_0 + \beta_1(x) \quad [2]$$

In other words, the average value of Y (corrosion rate) for any given x,y,z (temperature and partial pressure of CO_2) lies right on the regression line. The same principle applies in multiple regressions. Instead of a line, however, taking the expected value of the experimental equation results in what we call the true experimental plane or response surface:

$$yf(x) = \beta_0 + \beta_1(x1_i) + \beta_2(x2_i) \quad [3]$$

As an example, a three-dimensional response surface can generate (i.e., having experimental population of data values in space.

Estimation

Like an experimental regression line, an experimental response surface can be estimated from a random sample of data. The sample response surface is given by the equation

$$f(x) = b_0 + b_1 \cdot x1 + b_2 \cdot x2 + \cdots + b_p \cdot xp \quad [4]$$

Along with corresponding residual errors

$$e_i = y_i - (b_0 + b_1 \cdot x1_i + b_2 \cdot x2_i + \cdots + b_p \cdot xp_i) \quad [5]$$

As in simple linear regression, the population parameters can be estimated of a multiple regression by the method of least squares.

Using live symbols, the first derivatives of the sum of squared residuals can be obtained.

$$SSE = \sum_i \left[y_i - (b_0 + b_1 \cdot x1 + b_2 \cdot x2 + \cdots + b_p \cdot xp)\right]^2 \quad [6]$$

$$\frac{d}{db_0}\left[\sum_i [y_i - (b_0 + b_1 \cdot x1_i + b_2 \cdot x2_i)]^2\right] \quad [7]$$

$$\frac{d}{db_1}\left[\sum_i [y_i - (b_0 + b_1 \cdot x1_i + b_2 \cdot x2_i)]^2\right] \quad [8]$$

$$\frac{d}{db_2}\left[\sum_i [y_i - (b_0 + b_1 \cdot x1_i + b_2 \cdot x2_i)]^2\right] \quad [9]$$

Setting the resulting equations equal to zero and rearranging

$$\sum(-2 \cdot y + 2 \cdot b_0 + 2 \cdot b_1 \cdot x1 + 2 \cdot b_2 \cdot x2 + 2 \cdot b_3 \cdot x3) = 0 \quad [10]$$

$$\sum[-2\cdot(y-b_0-b_1\cdot x1-b_2\cdot x2-b_3\cdot x3)\cdot x1]=0 \quad [11]$$

$$\sum[-2\cdot(y-b_0-b_1\cdot x1-b_2\cdot x2-b_3\cdot x3)\cdot x2]=0 \quad [12]$$

$$\sum[-2\cdot(y-b_0-b_1\cdot x1-b_2\cdot x2-b_3\cdot x3)\cdot x3]=0 \quad [13]$$

Leads to the normal equations for the multiple regression

$$n\cdot b_0+b_1\cdot\sum x1+b_2\cdot\sum x2+b_3\cdot\sum x3=\sum y \quad [14]$$

$$b_0\cdot\sum x1+b_1\cdot\sum x1^2+b_2\cdot\sum((x1\cdot x2))=\sum((x1\cdot y)) \quad [15]$$

$$n\cdot b_0+b_1\cdot\sum x1+b_2\cdot\sum x2=\sum y \quad [16]$$

$$b_0\cdot\sum x1+b_1\cdot\sum\overrightarrow{x1^2}+b_2=\sum\overrightarrow{(x1\cdot x2)}=\sum\overrightarrow{(x1\cdot y)} \quad [17]$$

$$b_0\cdot\sum x2+b_1\cdot\sum(\overrightarrow{x2\cdot x1})+b_2\cdot\sum\overrightarrow{x2^2}=\sum(\overrightarrow{x2\cdot y}) \quad [18]$$

Produces the least squares estimates

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \end{pmatrix} := \mathrm{Find}(b_0, b_1, b_2).$$

The final equation is:

$$CR=b_0+b_1x_1+b_2x_2 \quad [19]$$

since $x_1=T$, and $x_2=P_{co_2}$.

Therefore, the final model equation is:

$$CR=b_0+b_1T+b_2P_{co_2}. \quad [20]$$

Basis of the Regression Model

Models based on multiple linear regressions of data were considered from Equation (4)

$$CR=b_0+b_1T+b_2P_{co_2} \quad [21]$$

where, Y is the response or dependent variable, x_i are the independent variables, a_0 is the free parameter, a_i are the regression parameters or regression coefficients.

The final model based on multiple linear regressions of data was used. The model equation is:

$$CR=b_0+b_1T+b_2P_{co_2}.$$

The dependent variables considered are operating temperature (T) and partial CO_2 pressure (PCO_2). These variables were chosen based on their significance on corrosion. The dependent variable is corrosion rate (CR).

Statistical Analysis of the Data

Statistical analysis of the data was performed using Polymath. Multiple regression analysis was performed to come up with a regression equation that would be able to explain how the model could be augmented by knowing any possible relationships among each of the input variables and the output. The independent variables where first selected based on theory, that is based on their relationship with the dependent variables. Then they were screened by the computer using the Polymath linear regression.

RESULTS

The experimental results, simulated results and statistical analysis results are presented in Tables 1–6 and Figures 1–3.

TABLE 1
Corrosion data of operating temperature, partial pressure of CO_2, and corrosion rate of crude oil in oil and gas transportation facilities

Operating temperature (°C)	Partial pressure of CO_2 (bar)	Corrosion rate (mm/yr)
30	4	3.2
30	4	3.1
30	4	3.1
30	4	3.1
30	4	3.2
32	5	4.1
32	5	4.1
32	5	4
32	5	4
32	5	4.1
34	6	5.2
34	6	5.2
34	6	5.1
34	6	5.3
34	6	5.2
34	6	5.2
36	7	6
36	7	6
36	7	6.1
36	7	6
36	7	6.1
37	8	7.6
37	8	7.5
37	8	7.6
37	8	7.5
37	8	7.5

TABLE 2
Experimental and simulated corrosion rate

Experimental corrosion rate (mm/yr)	Simulated corrosion rate (mm/yr)
3.2	3.135849
3.1	3.135849
3.1	3.135849
3.1	3.135849
3.2	3.135849
4.1	4.121698
4.1	4.121698
4.0	4.121698
4.0	4.121698
4.1	4.121698
5.2	5.107547
5.2	5.107547
5.1	5.107547
5.3	5.107547
5.2	5.107547
5.2	5.107547
6.0	6.093396
6.0	6.093396
6.1	6.093396
6.0	6.093396
6.1	6.093396
7.6	7.54
7.5	7.54
7.6	7.54
7.5	7.54
7.5	7.54

TABLE 3
Experimental and simulated corrosion rate against temperature and pressure

Temperature (°C)	Pressure (bar)	Experimental corrosion rate	Simulated corrosion rate
30	4	3.2	3.135849
30	4	3.1	3.135849
30	4	3.1	3.135849
30	4	3.1	3.135849
30	4	3.2	3.135849
32	5	4.1	4.121698
32	5	4.1	4.121698
32	5	4	4.121698
32	5	4	4.121698
32	5	4.1	4.121698
34	6	5.2	5.107547
34	6	5.2	5.107547
34	6	5.1	5.107547
34	6	5.3	5.107547
34	6	5.2	5.107547
34	6	5.2	5.107547
36	7	6	6.093396
36	7	6	6.093396
36	7	6.1	6.093396
36	7	6	6.093396
36	7	6.1	6.093396
37	8	7.6	7.54
37	8	7.5	7.54
37	8	7.6	7.54
37	8	7.5	7.54
37	8	7.5	7.54

DISCUSSION OF RESULTS

Mathematical model of corrosion prediction in oil and gas transportation facilities in the Niger Delta has been developed.

Figure 1 shows the corrosion data collected from Kaduna Refining and Petrochemical Company on experimental study carried out on corrosion rate with respect to operating temperature of the crude passing through transportation pipe and partial pressure of CO_2 in the crude. The corrosion data in Table1 was used for the development of corrosion prediction model equation obtained in this work. The results of the plot of temperature against corrosion rate (Figure 1) shows that the operating temperature of the fluid in the pipe has effect on corrosion rate in the pipe. This is in agreement with literature.[5]

The plot of partial pressure of CO_2 in the corrosion fluid against corrosion rate (Figure 2) shows that the partial pressure of CO_2 has effect on corrosion rate of crude oil transportation facilities. This is also in agreement with literature.[5]

Figure 2 shows the experimental and simulated corrosion rate against operating temperature. The plot shows that there is a near linear relationship between the corrosion rate and the temperature. This is in agreement with the de Waard model and corrosion rate monograph.[5]

Polymath, mathematical software packages for solving simulation problems has been chosen over the traditional

TABLE 4
Statistical analysis of correlation coefficients of the model equation

Variable	Value	95% confidence
a0	9.329057	2.720288
a1	−0.4607547	0.1180615
a2	1.907358	0.2138436

Model equation: $CR = a0 + a1^{*}T + a2^{*}P$.

TABLE 5
Statistical precision analysis of the model equation

R^2	0.9973989
2^2adj	0.9971727
Rmsd	0.0150276
Variance	0.0066374

approach of writing program in FORTRAN, Pascal and others because the algorithm of Polymath is based on mathematics compared to the traditional programming languages that are abstract. It makes the corrosion engineer focus on the real problem of corrosion engineering fundamentals involved and not concentrating on any foreign language that is not mathematics.

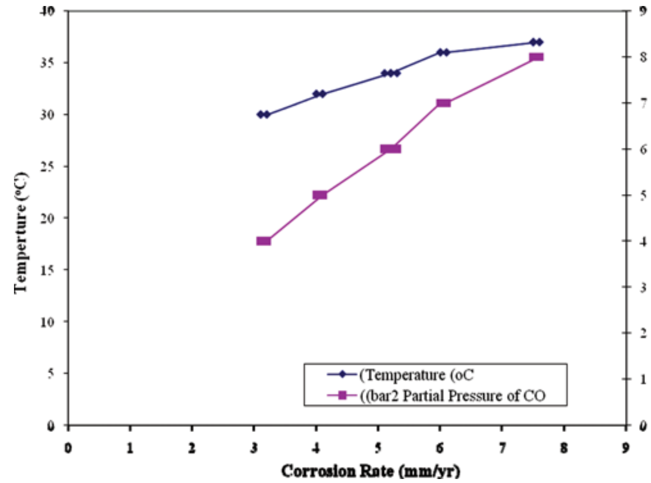

FIG. 1. Plot of corrosion data of operating temperature and partial pressure of CO_2 against corrosion rate of crude oil in oil and gas transportation facilities.

TABLE 6
Source data points and calculated data points

SN	Experimental corrosion rate (mm/yr)	Simulated corrosion rate (mm/yr)	Difference between experimental and simulated corrosion rate (mm/yr)
1	3.2	3.135849	0.0641509
2	3.1	3.135849	−0.0358491
3	3.1	3.135849	−0.0358491
4	3.1	3.135849	−0.0358491
5	3.2	3.135849	0.0641509
6	4.1	4.121698	−0.0216981
7	4.1	4.121698	−0.0216981
8	4	4.121698	−0.1216981
9	4	4.121698	−0.1216981
10	4.1	4.121698	−0.0216981
11	5.2	5.107547	0.0924528
12	5.2	5.107547	0.0924528
13	5.1	5.107547	−0.0075472
14	5.3	5.107547	0.1924528
15	5.2	5.107547	0.0924528
16	5.2	5.107547	0.0924528
17	6	6.093396	−0.0933962
18	6	6.093396	−0.0933962
19	6.1	6.093396	0.0066038
20	6	6.093396	−0.0933962
21	6.1	6.093396	0.0066038
22	7.6	7.54	0.06
23	7.5	7.54	−0.04
24	7.6	7.54	0.06
25	7.5	7.54	−0.04
26	7.5	7.54	−0.04

Polymath also allows the user to focus on the problem as it does the mathematical crunching and allow the user do corrosion engineering thinking of solving the problem. For the following reason, polymath has been used in simulation of the experimental result to obtain the mathematical model.

Table 5 shows the statistical precision analysis of the model equation. The R-square (coefficient of determination) value obtained was 99.74%, which highly suggests that the relationship between the predictor and response variables is linear. The R-square value of 99.74% implies that only 99.74% of the variability in the output could be captured and explained by this model. The adjusted

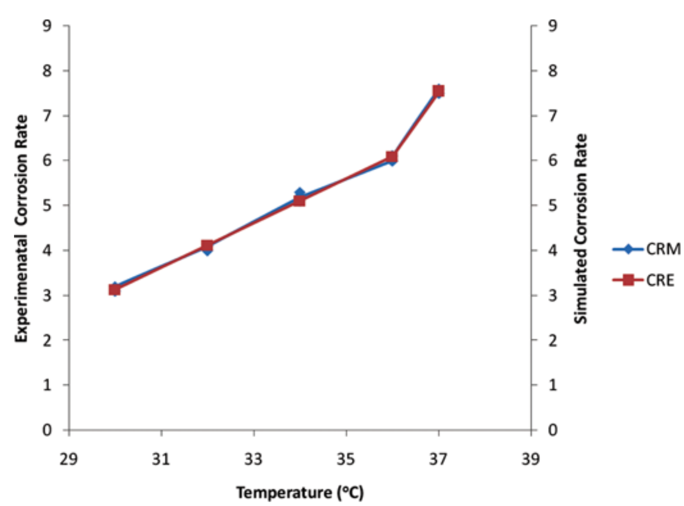

FIG. 2. Plot of experimental corrosion rate (mm/yr) and simulated corrosion rate (mm/yr) against partial pressure of CO_2 (bar).

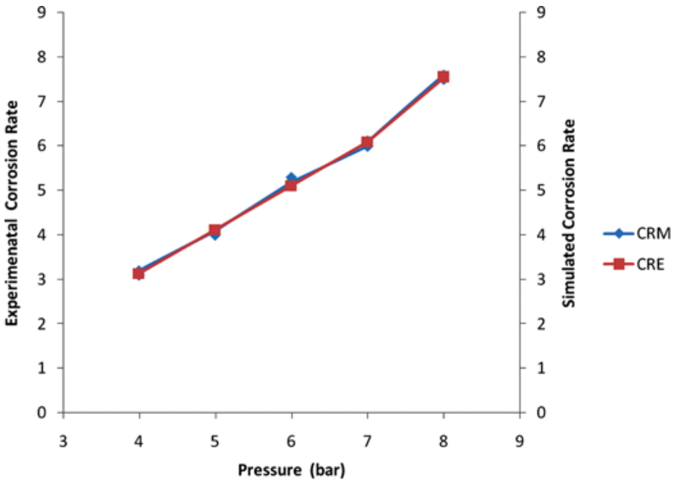

FIG. 3. The plot of experimental corrosion rate (mm/yr) and simulated corrosion rate (mm/yr) against partial pressure of CO_2 (bar).

R-square (adjusted coefficient of determination) value obtained was 99.69%, which highly suggests that the relationship between the predictor and response variables is linear. The adjusted R-square value of 99.74% implies that only 99.74% of the variability in the output could be captured and explained by this model. Table 3 shows that variation in the model equation is 0.0066374. The low value of the variance shows that the model is accurate.

The slight deviation of the simulated result was as a result of the model assumptions. In order to manage the scope of the work and to prevent ambiguity, certain assumptions were made to enhance simplicity and ease of application. Some of these assumption were rather more ideal than real.

CONCLUSION

From the simulation result obtained, it was observed that there are remarkable agreement between the experimental result and the simulation result for the results obtained for corrosion prediction model developed for crude oil transportation pipeline used in the Niger Delta region of Nigeria. The model develop is also in total agreement with that developed by de Waard.[5]

The statistical model developed is:

$$CR = -9.329057 - 0.4607547\,T + 1.907358\,PCO_2$$

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