Application of Response Surface Methodology and NORSOK Simulation Software for Modeling and Optimizing Corrosion Penetration Rate in Crude Oil Pipelines

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Abstract:

This study aims to investigate the effects of temperature, pressure, flow rate, and pH on the corrosion penetration rate (CPR) of pipelines used for transferring crude oil. The corrosion penetration rate is intended to be the dependent variable and the input parameters are independent variables in the mathematical model. The response surface methodology was applied to the model to determine the optimal values of these parameters. The tests were simulated using NORSOK software, which was also used to determine the corrosion penetration rate for each experiment.

Using Minitab 17 software, the experiments were developed based on the central composite experimental design (CCD). The constructed mathematical model was tested for conformance, using the mean absolute percentage error. It had a value of 1%. Therefore, this indicates that the developed mathematical model was consistent.

1.2246 mm/year was determined to be the optimal value for the corrosion penetration rate, which was computed numerically using the RSM model. The operational parameters included temperature (126 F), pressure (195 psi), pH (5.6443), and shear stress (1 psi).

Keywords: NORSOK software; Corrosion penetration rate; RSM; MAPE.

الملخص

تهدف هذه الدراسة إلى التحقق من تأثيرات درجة الحرارة والضغط ومعدل التدفق، الرقم الهيدروجيني على معدل اختراق التآكل (CPR)لخطوط الأنابيب المستخدمة لنقل النفط الخام. يكون المتغير التابع هو معدل اختراق التآكل وأن تكون هذه المدخلات المؤثره كمتغيرات مستقلة في النموذج الرياضي. تم تطبيق منهجية الاستجابة السطحية على النموذج لتحديد القيم المثلى لهذه المتغيرات. تمت محاكاة الاختبارات باستخدام برنامجNORSOK ، والذي تم استخدامه أيضًا لتحديد معدل اختراق التآكل لكل تجربة. باستخدام برنامج Minitab 17 تم تصميم التجارب على أساس التصميم المركب المركزي .(CCD) وتم اختبار توافق

وملائمة النموذج الرياضي الذي تم بنائه باستخدام متوسط النسبة المئوية للخطأ المطلق. وكانت قيمتها 1%. ولذلك فإن هذا يدل على أن النموذج الرياضي الذي تم بنائه كان متسقا.

تم تحديد 1.2246 مم/سنة لتكون القيمة المثلى لمعدل اختراق التآكل، والتي تم حسابها رقميًا باستخدام نموذج RSM. وشملت المتغيرات التشغيلية درجة الحرارة (126 فهرنهايت)، والضغط (195 رطل لكل بوصة مربعة)، الرقم الهيدروجيني (5.6443)، واجهاد القص (1 رطل لكل بوصة مربعة).

الكلمات المفتاحية : برنامج NORSOK؛ معدل اختراق التآكل. طريقة الاستجابة السطحية , متوسط نسبة الخطأ المطلق .

I. INTRODUCTION

The transportation of heavy and extra-heavy crude oils from the head well to the refinery is becoming important since their production is currently rising all over the world. Such oils are characterized by a low API gravity (< 20) and high viscosity (> 103 cP at 298.15 K) that render difficult oil flow through pipelines. Conventional technology pipelining is designed for light and medium oil crudes. Still, the pipelining of heavy and extra-heavy crude oils may be challenging because of their high viscosities, asphaltene and paraffin deposition, increasing formation water content, salt content, and corrosion issues [Nesic et al, 2007].

One of the necessities of an effective oil and gas pipeline safety Management Plan (SMP) is the establishment of a safe and efficient risk assessment strategy for pipelines where the significant danger is corrosion. Corrosion growth is related to several factors involving pipe material, pipe condition, and defect geometrical imperfection. Thus, the assurance of a proper corrosion assessment requires the prediction and evaluation of corrosion growth rates. The prediction of corrosion growth rate precisely would minimize the cost of pipeline maintenance through the determination of the deteriorated pipeline segments. In-line inspection (ILI) has been used to detect the pipeline's corrosion, also the corrosion can be detected by other inspection tools such as Magnetic flux leakage (MFL) and Ultrasonic tool (UT). However, there are numerous models have been utilized to anticipate the corrosion growth rate such as deterministic and probabilistic models. Recently, there have been conducted researches on the application of artificial intelligence in predicting corrosion growth rate for oil and gas pipelines such as artificial neural network (ANN) and fuzzy logic (FL)[Ivan S. et al, 2011].

Corrosion in lubricate and vapor enterprises principally handles CO2 gas as it is the main cause of disappointment in the stream subdivision of the lubricate and smoke manufacturing of pipelines from element fortify that has advantages in conditions of chance, cost, and ease of lie over additional alloys. Unfortunately, element brace has lower fighting to colorless odorless gas disintegration. In addition, some differing bitter classes are present in the lubricate field accompanying interplay 'tween ruling class, to a degree temperature, pH, flow rate (m/s), CO2 partial pressure, and tart acid (HAc), and CO2. The vicinity of element dioxide (CO2) in the fluid steps up the disintegration rate on account of the allure reaction accompanying water that results in making carbonic acid [Nesic s et al, 2007].

Based on former experiments, it was proved that when CO2 is separated in water; three types of responses concede possibility occurs to a degree the assimilation, photoelectric and photoelectric responses, and backlashes superior to the establishment of a group of chemical elements and carbonate (FeCo3) layers upon brace namely famous expected alive in acid answer therefore, water pH is discounted and causes corrosion on element brace [Ivan S. et al, 2011].

Many research documents are vacant on CO2 disintegration indicators and the belongings of variety like HAc accompanying several different operating limits containing hotness, pH, and flow rate [Mokhtar I 2005],[Zhang G 2009]. Most of the indicator models depended on particular algorithms to connect individual effects of the communicating species to produce a representative total disintegration rate. The individual effect is persistent from the exploratory routine of property fixed sure variables and changeful the principles of another variable. This exploratory arrangement was wasteful and needed a lot of experiments to process all likely disintegration dossier. In addition, the prophecy does not completely cover representing the dossier together [Vanssa et al 2007]. In this paper, a mathematical model was developed to predict the effect of operating parameters of the crude oil transportation process on CO2 corrosion rate by using RSM.

II. LITERATURE REVIEW

The study by Senussi et al focuses on implementing a backpropagation artificial neural network approach to develop a model capable of accurately predicting the CO2 corrosion penetration rate (CPR) under specific operating parameters [Senussi et al 2021]. The authors successfully developed a model that maps input parameters such as pH, temperature, pressure, and shear stress to CPR and demonstrated that the backpropagation network (BPN) could adjust its weight coefficients with a small set of examples, indicating the generation of proper output. The developed BPN model was validated using mean absolute errors (MAE), with a value of 0.00457 mm/y, signifying the accuracy and reliability of the model.

Bushra et al. developed a model (Fuzzy Logic) to predict the CO2 erosion, sweet environment, and penetration rate (CPR) of the Libyan Arabian Gulf Oil Company (AGOCO) Sariir-Tobruk

steel pipeline [Bushra et al. 2018]. The study was conducted with different values of the most important operating parameters; Temperature (112,126 °F), pressure (195-494 psi), and pH (5.51-5.65). MINITAB software version was used to design experiments (DOE), fuzzy logic was developed using MATLAB (2013) Toolbox to predict CO erosion penetration rate (CPR), and NORSOK M-506 software was used as simulation tool to calculate CPR for each experiment. It was found that the expected CO2 corrosion penetration rate was very close to that calculated using NORSOK M-506 with a mean absolute error (MAE) of 0.01. Therefore, it can be concluded that Fuzzy Logic is a promising technology that can be used with confidence in the prediction of CPR during transportation of crude oil through the steel pipeline. The study by Sulyman et al. focuses on investigate the influence of a number of related parameters namely temperature, pressure,
flow rate and pH on the corrosion penetration rate (CPR) of crude oil transportation process by pipelines [Sulyman et al 2023]. It intends the mathematical model of these parameters as independent variables with corrosion penetration rate as a dependent variable. The model was used to establish the best values of these parameters using the response surface methodology. Aspen HYSYS software was utilized to simulate the experiments and to calculate the corrosion penetration rate for each experiment. The experiments designed based on the central composite experimental design (CCD) using Minitab 17 software. The mean absolute percentage error was used to determine the conformance of the developed mathematical model. Its value was 0.02%, this indicates that the developed mathematical model was consistent. The Nash Sutcliffe efficiency (NSE) was also calculated. Its value was 0.999 which confirms the high-efficiency of the model. The optimal corrosion penetration rate conditions were determined, temperature (100°F), pressure (360 psig), flow rate (150,000 bbl/day), and pH (5.65). Accordingly, the minimum corrosion penetration rate is (3.98 mm/year).

III. METHODOLOGY

A. Material

Many elements influence CPR. The influence of the factors temperature, pressure, shear stress, and pH on the corrosion penetration rate was investigated in this study utilizing RSM. The pipeline considered in this study is according to AGOCO from the Sarir field to Hrayqa oil port in Tobruk, the entire distance of the pipeline is 514 km, the pipeline diameter is 34 inches, and the mole percent of CO2 Modeling and Optimization of Corrosion Penetration Rate in Crude Oil Pipeline using Response Surface Methodology based on NORSOK Simulation Software set at 0.8% for the period between 01/01/2019 and 01/01/2023 for oil pipeline.

B. Response Surface Methodology

Response Surface Methodology (RSM) is an optimization approach that utilizes a combination of mathematical and statistical techniques to construct an empirical model. By employing well-designed experiments, the objective of RSM is to optimize a specific output variable, known as the response, which is influenced by various independent input variables. These experiments involve systematically altering the input variables to observe and evaluate their impact on the output response. The Central Composite Design (CCD) is developed through sequential experimentation. It consists of a factorial point (from a design) k represents the number of the factors, central point, and axial points. During the experimentation, if the first-order model lacks fit evidence, axial points are subsequently added to quadratic terms, producing more center points to develop CCD. Two parameters from the CCD design running from the design center are the number of center points m at the origin and the distance α of the axial runs.
As there are four input parameters namely, temperature, pH, pressure, and shear Stress. The output response selected for these experiments was tensile strength. The upper (+1) and lower (-1) levels of all the four parameters and their designations are shown in table .1.

Table 1. The levels of process parameters

Variable	Units	Notation	Low	High
Temperature	ºF	X_1	112	126
Pressure	Psi	X_2	195	494
pH	---	X_3	5.51	5.65
Shear Stress	Psi	X_4	1	30

In this work, the variables considered are those most critical to CPR; temperature, pressure, pH, and Shear Stress. The experimental design was conducted according to the CCD method in the Minitab 17 program for four factors and one response. CCD determined total experimental runs of 31 as shown in table 2. To carry out these experiments, the reality was simulated using NORSOK.

Table 2: Design of Experiment and its Actual Values of CPR

T (F)	P (psi)	Hp	S (psi)	Actual CPR mm/yr
119	344.5	5.58	15.5	2.8
112	195	5.65	30	2.1
119	344.5	5.58	15.5	2.8
119	344.5	5.545	15.5	2.9
112	195	5.51	30	2.4
119	344.5	5.58	15.5	2.8
119	344.5	5.615	15.5	2.7
119	269.75	5.58	15.5	2.4
119	344.5	5.58	15.5	2.8
112	494	5.65	1	2.2
112	494	5.51	30	4.2
126	494	5.51	30	3.9
119	344.5	5.58	15.5	2.8
119	344.5	5.58	15.5	2.8
126	195	5.51	1	1.5
126	494	5.65	30	3.3
112	195	5.65	1	1.4
122.5	344.5	5.58	15.5	2.7
126	494	5.51	1	2.4
115.5	344.5	5.58	15.5	2.8
119	419.25	5.58	15.5	3.1
126	195	5.51	30	2.3
112	494	5.65	30	3.6
119	344.5	5.58	8.25	2.6
126	195	5.65	1	1.2
126	195	5.65	30	1.9
112	195	5.51	1	1.5
119	344.5	5.58	15.5	2.8
112	494	5.51	1	2.6
119	344.5	5.58	22.75	2.9
126	494	5.65	1	2.1

C. Results

The response data were calculated by the NORSOK model. Then, the data were entered in the Minitab worksheet, and after that, the predicted values of CPR were calculated as shown in Table 3.

Tables 3: Actual Values by NORSOK Model and Predicted Values by RSM

T (F)	P (psi)	Hp	S (psi)	Actual CPR mm/yr	Prediction CPR mm/yr
119	344.5	5.58	15.5	2.8	2.79
112	195	5.65	30	2.1	2.08
119	344.5	5.58	15.5	2.8	2.79
119	344.5	5.545	15.5	2.9	2.90
112	195	5.51	30	2.4	2.43
119	344.5	5.58	15.5	2.8	2.79
119	344.5	5.615	15.5	2.7	2.71
119	269.75	5.58	15.5	2.4	2.44
119	344.5	5.58	15.5	2.8	2.79
112	494	5.65	1	2.2	2.25
112	494	5.51	30	4.2	4.16
126	494	5.51	30	3.9	3.91
119	344.5	5.58	15.5	2.8	2.79
119	344.5	5.58	15.5	2.8	2.79
126	195	5.51	1	1.5	1.47
126	494	5.65	30	3.3	3.31
112	195	5.65	1	1.4	1.37
122.5	344.5	5.58	15.5	2.7	2.71
126	494	5.51	1	2.4	2.45
115.5	344.5	5.58	15.5	2.8	2.80
119	419.25	5.58	15.5	3.1	3.07
126	195	5.51	30	2.3	2.28
112	494	5.65	30	3.6	3.61
119	344.5	5.58	8.25	2.6	2.49
126	195	5.65	1	1.2	1.27
126	195	5.65	30	1.9	1.88
112	195	5.51	1	1.5	1.52
119	344.5	5.58	15.5	2.8	2.79
112	494	5.51	1	2.6	2.60
119	344.5	5.58	22.75	2.9	3.03
126	494	5.65	1	2.1	2.05

The data was entered into the Minitab worksheet, after which the probabilistic values that determine whether effects are significant or non-significant are shown in Table 4.

Table 4. Analysis of variance for CPR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	13.6357	0.97398	303.27	0.000
X1	1	0.1274	0.12742	39.68	0.000
X2	1	6.4923	6.49227	2021.53	0.000
X3	1	0.5824	0.58242	181.35	0.000
X4	1	4.8547	4.85470	1511.63	0.000
X1*X1	1	0.0035	0.00351	1.09	0.312
X2*X2	1	0.0035	0.00351	1.09	0.312
X3*X3	1	0.0005	0.00050	0.16	0.698
X4*X4	1	0.0035	0.00351	1.09	0.312
X1*X2	1	0.0100	0.01000	3.11	0.097
X1*X3	1	0.0025	0.00250	0.78	0.391
X1*X4	1	0.0100	0.01000	3.11	0.097
X2*X3	1	0.0400	0.04000	12.45	0.003
X2*X4	1	0.4225	0.42250	131.56	0.000
X3*X4	1	0.0400	0.04000	12.45	0.003
Error	16	0.0514	0.00321		
Total	30	13.6871			

The equation of the estimated regression coefficients for improving MRR of a first- and second-order weld joint is as Equation .1:

$$Y = 291 + 0.847\, X1 + 0.03701\, X2 - 122\, X3 + 0.3372\, X4 - 0.00296\, X1{*}X1$$
$$- 0.000006\, X2{*}X2 + 11.2\, X3{*}X3 - 0.000690\, X4{*}X4 - 0.000024\, X1{*}X2 - 0.0255\, X1{*}X3$$
$$- 0.000246\, X1{*}X4 - 0.00478\, X2{*}X3 + 0.000075\, X2{*}X4 - 0.0493\, X3{*}X4. \quad (1)$$

D Validation Model

To validate the developed model, the mean absolute percentage error (MAPE) was used to estimate the variation between the actual and predicted CPR. The value of the MAPE is 1%, compared with the actual values of Corrosion Penetration Rate, as plotted in Fig 1.

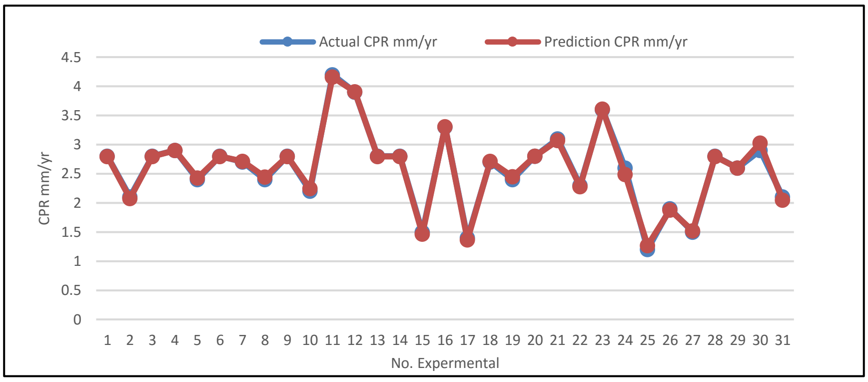

Fig.1: The Actual and the Predicted CPR

D Optimization of CPR

As given in Fig. 2, the minimum CPR conditions were determined as, temperature (126 F), pressure (195 psi), pH (5.6443). and Shear Stress (1 psi) Accordingly, the maximum CPR is 1.2664 mm/yr .

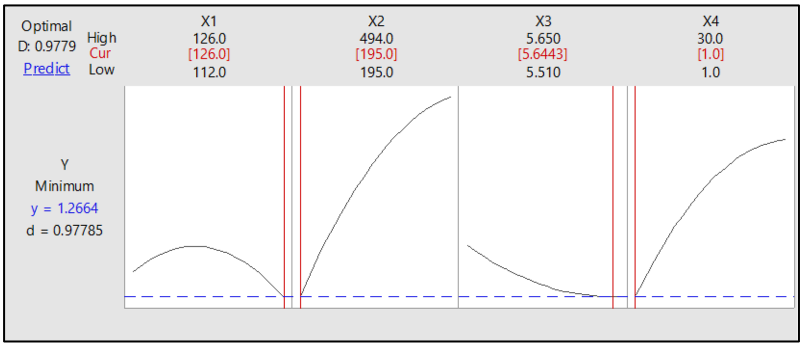

Fig 2. Optimization CPR

V. Conclusion

In this study, attempts were made to predict the corrosion penetration rate of the pipelines that are used for transporting crude oil between Sarir-Tobruk stations. The corrosion penetration rate values were determined by using NORSOK software. *The following points summarize the conclusions of the study:*

1. Based on ANOVA analysis, the four factors considered had significant effects on the corrosion penetration rate, as well as the interaction between (shear stress and pH), (pressure and shear stress) and (pressure and pH) had significant effect on corrosion penetration rate, while the interaction (temperature and pH) were insignificant. However, all the quadratic were insignificant.

2. Based on the comparison between the actual values of corrosion penetration rate calculated by using NORSOK software and the predicted values of corrosion penetration rate by using the

RSM technique, it can be concluded that the RSM model could be used to predict the values of corrosion penetration rate, under the specified parameters ranges, with a mean absolute percentage error of 1%.

3. The optimal value for the numerically calculated corrosion penetration rate using the RSM model, was found to be 1.2246 mm/year, with operating parameters values of temperature (126 F), pressure (195 psi), pH (5.6443). and Shear Stress (1 psi).

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