MODELING AND PREDICTION OF CO_2 CORROSION PENTRATION RATE OF PIPELINE USING FUZZY LOGIC TECHNIQUE

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الملخص

الغرض من هذه الدراسة هو النمذجة والتنبؤ باستخدام طريقة المنطق الضبابى (Fuzzy Logic) لمعدل الاختراق الناتج عن التآكل فى وجود غاز ثانى اكسيد الكربون فى خط انابيب نقل النفط الخام من السرير الى طبرق المملوك لشركة الخليج العربى للنفط والاستكشاف بليبيا. الدراسة أخذت فى الاعتبار تأثير عوامل مختلفة مثل درجة الحرارة (112-126°F) والضغط (195-494 Psi) والرقم الهيدروجينى (5.51-5.65). فى هذه الدراسة استخدم برنامج MINITAB لتصميم تجارب عند ظروف تشغيل افتراضية تحاكى الظروف الحقيقية كما استخدم برنامج MATLAB (2013) لتصميم نموذج المنطق الضبابى لحساب معدل الاختراق ومقارنته بالقيم المحسوبة من قبل شركة الخليج باستخدام برنامج Norsok M-506 وقد اظهرت النتائج تطابق فى القيم وبمعدل خطأ مطلق يساوى 0.01 . الدراسة توصى باستخدام طريقة المنطق الضبابى لنمذجة ومن ثم التنبؤ بمعدل التآكل الذي يحدث في انابيب الصلب الناقلة للنفط الخام.

ABSTRACT

In this study, an attempt was made to develop (Fuzzy Logic) model to predict CO_2 corrosion, sweet environment, penetration rate (CPR) of the Libyan Arabian Gulf Oil Company (AGOCO) Sarir-Tobruk steel pipeline. The study was conducted at different values of the most significant operating parameters; temperature (112-126°F), pressure (195-494 psi) and pH (5.51-5.65). The MINITAB software version16 was used to design the experiments (DOE), Fuzzy logic was developed using MATLAB (2013) Toolbox to predict CO_2 corrosion penetration rate (CPR) and NORSOK M-506 software was used as a simulation tool to calculate CPR for each experiment. It was found that, the predicted CO_2 corrosion penetration rate was very close to that calculated using NORSOK M-506 with a Mean Absolute Error (MAE) of 0.01. Therefore, it could be concluded that Fuzzy Logic is a promising technique that could be used confidently in predicting the CPR during transporting the crude oil through the steel pipeline.

KEYWORDS: CO_2 corrosion penetration rate (CPR); Prediction; Fuzzy Logic.

INTROUDCTION

Corrosion is a problem in almost all industries. That makes maintenance, repair and replacement of damaged parts cost make up a significant part of the economy. For example, the global cost of corrosion is estimated to be US$ 2.5 trillion, which is equivalent to 3.4% of the global Gross Domestic Product (GDP) (2013) [1]. $12 billion dollars/year are related directly to the transportation lines of the oil and gas industry [2]. In oil and gas industry, carbon dioxide (CO_2) is present during the production and the transportation. This makes CO_2 corrosion (sweet environment) penetration a severe problem in oil field. The hydration of CO_2 to carbonic acid can decrease pH and cause corrosion of mild steel. Degree of corrosiveness due to CO_2 gas is influenced by environmental conditions such as; temperature, CO_2 partial pressure, corrosion film properties and flow conditions [2]. Many studies are conducted on the corrosion caused by CO_2 in aqueous phases [3-6].

The successful application of carbon steels in oil and gas industry in carbon dioxide (CO_2) containing environments depends mainly on either the formation of protective corrosion product film or the use of corrosion inhibitors. The corrosion mechanism of carbon steel in environments containing CO_2 is complex and it may lead to general or localized corrosion and corrosion cracking [7]. Oil and associated products are transported through pipe lines from producing to consuming areas, including across provincial and international boundaries. The oil is piped to refineries where it is converted into petroleum products. In this study, the crude oil transportation lines between platforms in the AGOCO was investigated as a case study. The produced crude oil is transported for (513.6 km) in (34") pipeline from Sarir to Tobruk. Prediction of corrosion behavior is important in design stage to select materials for construction and to maintain operations integrity. There are many models developed by industries for CO_2 corrosion prediction. Such models can give accurate predictions, but it is valid only in specific conditions. Since different results may be obtained from the same case, the understanding of the basis of developed model is required to interpret corrosion data meaningfully. Although the understanding of pure CO_2 corrosion is well accepted, the corrosion mechanism with the presence of other species such as acetic acid (HAc) is unclear. The problem is further complicated as the corrosion can be influenced not only by various reservoir species, but also by operational parameters such as temperature, pH, and flow condition. The complex interactions of various species and operating condition pose a challenge in the corrosion prediction. The technical accuracy of corrosion prediction based on the fact that prediction model treats the possible interactive effects of these variables [8]. Many studies were conducted to predict CO_2 corrosion and to study the effects of species like HAc with several other operating parameters including temperature, pH, and flow rate condition [7,9-14]. Most of the predicted models rely on specific algorithms to combine individual effect of the interacting species to produce a representative total corrosion rate.

The individual effect was determined from the experimental routine of holding certain variables as constants and changing the values of another variable. This experimental method is inefficient and needs a large number of experiments to process all possible corrosion data. In this paper, a mathematical model was developed to predict the effect of operating parameters of the crude oil transportation process on CO_2 corrosion rate by using fuzzy logic technique.

ANALYSIS OF VARIANCES (ANOVA).

In this paper, the initial techniques of the analysis of variance were developed by the statistician and geneticist R. A. Fisher in the 1920s and 1930s and are sometimes known as Fisher's ANOVA or Fisher's analysis of variance, due to the use of Fisher's F distribution as part of the test of statistical significance. The response surface methodology (RSM) is also used to analyze the effect of the selected parameters on the response, e.g. (CPR). Central composite design (CCD), one of the primary design techniques in RSM, was selected in this study. Many parameters affect the CO_2

corrosion penetration rate of the Sarir-Tobruk pipeline. Table (1) shows the operating parameters selected in this study and their corresponding ranges and Table (2) shows the chemical composition of the API 5L X52 steel.

Table 1: The operating parameters and corresponding ranges

Parameter	Notation	Unit	Range	
			Lower value	Upper value
Temperature	Temp	F°	112	126
Pressure	P	Psi	195	494
pH	pH	-	5.51	5.65

Table 2: The chemical composition in wt.% of the API 5L X52 steel

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu
0.16	0.45	1.10-1.60	0.025	0.005	0.20	0.08	0.20	0.04	0.20

FUZZY LOGIC TECHNIQUE

Fuzzy logic provides a method to formalize reasoning when dealing with vague terms. Traditional computing requires finite precision, which is not always possible in real world scenarios. Not every decision is either true or false, or as with Boolean logic is either 0 or 1. Fuzzy logic allows for membership functions, or degrees of truthfulness and falsehoods, or as with Boolean logic, not only 0 and 1 but all the numbers that fall in between them [15]. A Fuzzy Logic System (FLS) performs a nonlinear mapping of an input dataset to a scalar output data [16]. It consists of four main parts: fuzzufier, rules, inference engine and defuzzifier. The architecture of a FLS is shown in Figure 1. [14]

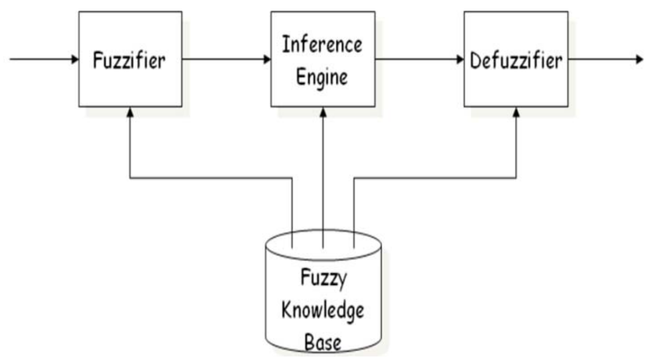

Figure 1: The architecture of a FLS

The steps involved in developing a FLS are as follows [13]:

Fuzzifier Converts the crisp input to a linguistic variable using the membership functions stored in the fuzzy knowledge base. Fuzzy linguistic variables are used to represent qualities spanning a particular spectrum; e.g. temperature spans are Freezing, Cool, Warm, or Hot. In-Ference Engine, Using IF-THEN type fuzzy rules converts the fuzzy input to the fuzzy output. Defuzzifier Converts the fuzzy output of the inference engine to crisp using membership functions analogous to the ones used by the fuzzifier. Fuzzy Knowledge Base Information storage for Linguistic variables definitions and Fuzzy rules [14].

KNOWLEDGE BASE

The input to a fuzzy system is called crisp input since it contains precise information about the parameters. The fuzzifier converts this precise quantity to an imprecise quantity like, 'large',,'medium' or ,'high' with a degree of belongingness. Typically, the value ranges from 0 to 1. A fuzzy rule is a simple IF-THEN rule with a condition and a conclusion. The knowledge base is the main part of a fuzzy system where both rule base and data base are jointly referred. The data base defines the membership functions of the fuzzy sets used in the fuzzy rules, while the rule base contains a number of fuzzy IF-THEN rules [14].

IMPLEMENTATION OF FUZZY LOGIC TECHNIQUE

To implement the fuzzy model and achieve the study goals, parameters and their values were fed to MINITAP16 software, a DOE model was generated with twenty runs coupled with specific parametric settings as shown in Table (3).

Table 3: Design of experiment and its calculated using NORSOK M-506 values of CPR

Run	Standard Order	Run Order	Point Type	Blocks	T (°F)	P (psi)	pH	Calculated CPR (mm/yr.)
1	16	1	0	1	119	344.5	5.58	2.1
2	12	2	-1	1	119	494.0	5.58	2.6
3	7	3	1	1	112	494.0	5.65	2.5
4	8	4	1	1	126	494.0	5.65	2.3
5	1	5	1	1	112	195.0	5.51	1.7
6	5	6	1	1	112	195.0	5.65	1.5
7	9	7	-1	1	112	344.5	5.58	2.2
8	18	8	0	1	119	344.5	5.58	2.1
9	15	9	0	1	119	344.5	5.58	2.1
10	20	10	0	1	119	344.5	5.58	2.1
11	14	11	-1	1	119	344.5	5.65	2
12	11	12	-1	1	119	195.0	5.58	1.6
13	3	13	1	1	112	494.0	5.51	2.9
14	4	14	1	1	126	494.0	5.51	2.7
15	10	15	-1	1	126	344.5	5.58	2.1
16	2	16	1	1	126	195.0	5.51	1.6
17	6	17	1	1	126	195.0	5.65	1.4
18	13	18	-1	1	119	344.5	5.51	2.3
19	19	19	0	1	119	344.5	5.58	2.1
20	17	20	0	1	119	344.5	5.58	2.1

The same parameters were reentered into NORSOK Norwegian standard M-506 software [17] (M-506 software used to calculate the CPR in AGOCO) to compare the predicted CPR, using fuzzy logic model, with the calculated, using NORSOK M-506. The CPR values were calculated in each run with 2.5% CO_2 mole percentage and 5 psi shear stress. The columns; Standard Order, Run Order, Point Type and Blocks contain optional information that you can specify in the MINITAP worksheet. The Analysis of

Variance (ANOVA) was made with help of MINITAB 16 software. Based on this analysis, the average loss could be determined by statistically averaging the quadratic loss. The average loss is proportional to the mean squared error of the response (CPR) about its target value. Table (4) shows the Analysis of Variance (ANOVA) for CPR response. From this table, the percentage influence of all factors on responses could be seen. The adjusted R-squared (R^2) values along with the F-test results and probability P-values were used to evaluate the results of the model equations. For example, P value less than 0.0500 indicates that model terms are significant. In this case T, P, pH, pH*P and P*T are significant model terms. Values of P greater than 0.1000 indicate that the model terms are not significant.

Table 4: Analysis of Variance (ANOVA)

Source	DF	Seq SS	Adj SS	Adj MS	F-test	P-value
Regression	9	3.01	3.01118	0.33458	379.42	0.000
Linear	3	2.98	2.97800	0.99267	1125.70	0.000
pH	1	0.23	0.22500	0.22500	255.15	0.000
P	1	2.70	2.70400	2.70400	3066.39	0.000
T	1	0.04900	0.04900	0.04900	55.57	0.000
Square	3	0.00818	0.00818	0.00273	3.09	0.076
pH*pH	1	0.00200	0.00006	0.00006	0.06	0.805
P*P	1	0.00612	0.00568	0.00568	6.44	0.029
T*T	1	0.00006	0.00006	0.00006	0.06	0.805
Interaction	3	0.02500	0.02500	0.00833	9.45	0.003
pH*P	1	0.02000	0.02000	0.02000	22.68	0.001
pH*T	1	0.00000	0.00000	0.00000	0.00	1.000
P*T	1	0.00500	0.00500	0.00500	5.67	0.039
Residual Error	10	0.00882	0.00882	0.00088		
Lack-of-Fit	5	0.00882	0.00882	0.00176		
Pure Error	5	0.00000	0.00000	0.00000		
Total	19	3.02000				

DF — degree of freedom; Seq SS — sequential sum of squares; Adj SS — adjusted sum of squares; Adj MS — adjusted mean squares.

SIMULATION OF FUZZY LOGIC

In the fuzzy logic system, the input is always a crisp numerical value limited to the universe of discourse of the input variable. The input crisp variables are temperature, pressure and pH see Figures (3-5). All the three input variables have been labeled and grouped into three levels: low, medium and high, and the output variable CPR is divided into five levels: very low, low, medium, high and very high as shown in Figure (6).

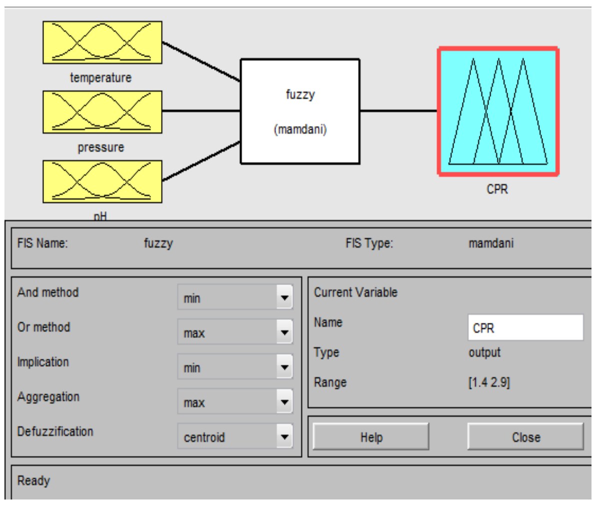

Figure 2: Input-output parameters for fuzzy logic control model

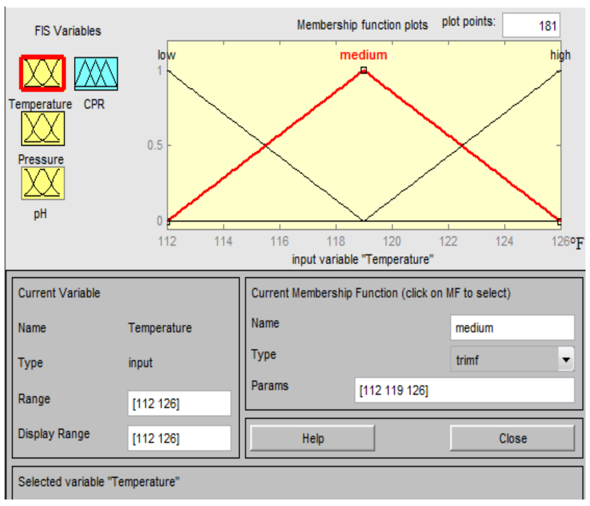

Figure 3: Membership function for (Temperature)

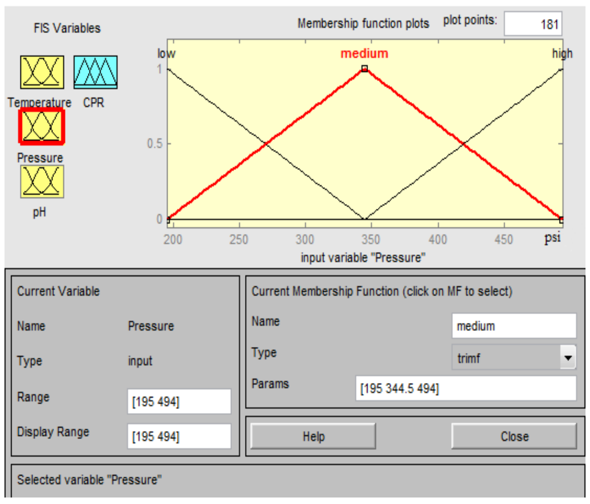

Figure 4: Membership function for (Pressure)

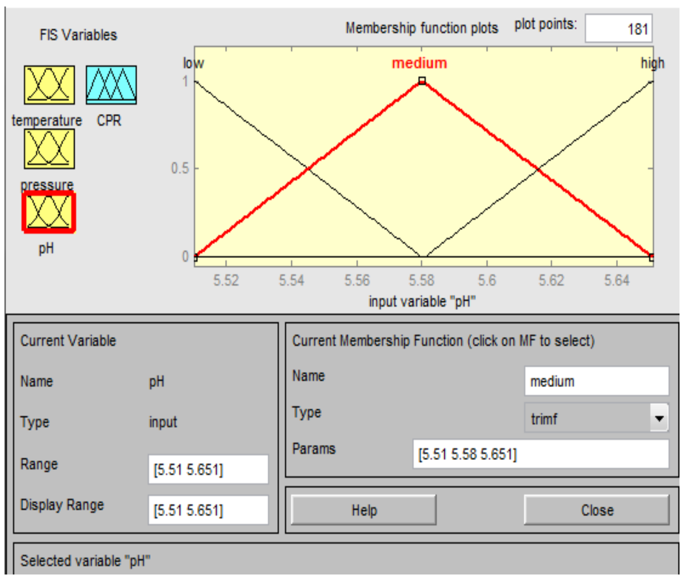

Figure 5: Membership function for (pH)

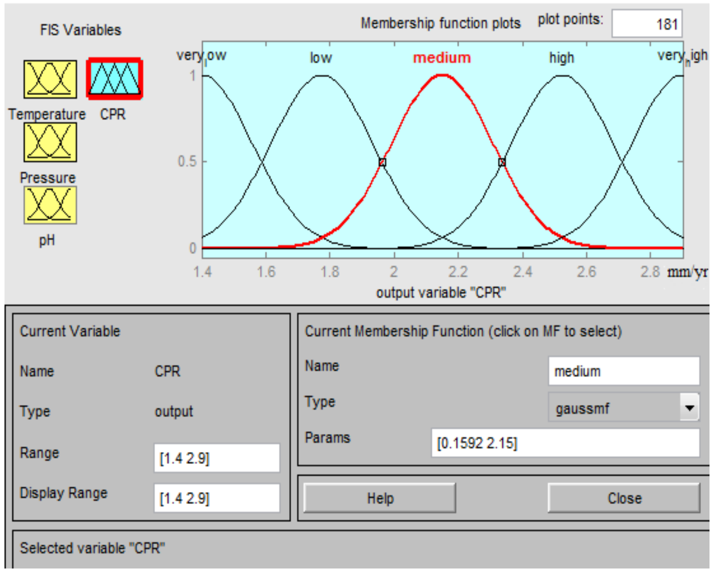

Figure 6: Membership function for (CPR)

The fuzzy logic system is based on rules and each of them depends on resolving the inputs into a number of different fuzzy linguistic sets. Before the rules were evaluated, the inputs were fuzzified according to each of these linguistic sets, and the degree to which each part of the antecedent was recommended for each rule. Every rule has a weight (number between 0 and 1) which is applied to the number given by the antecedent. Once proper weighting has been assigned to each rule, the implication method is implemented. The result is a fuzzy set represented by a membership function, which weights the linguistic characteristics that are attributed to it. The aggregates of a fuzzy set encompass range of output values (CPR) and so must be defuzzified in order to resolve a single output value from the set. Figure (7) shows the fuzzy rules of our case and Figure 8 shows Fuzzy logic simulation stages.

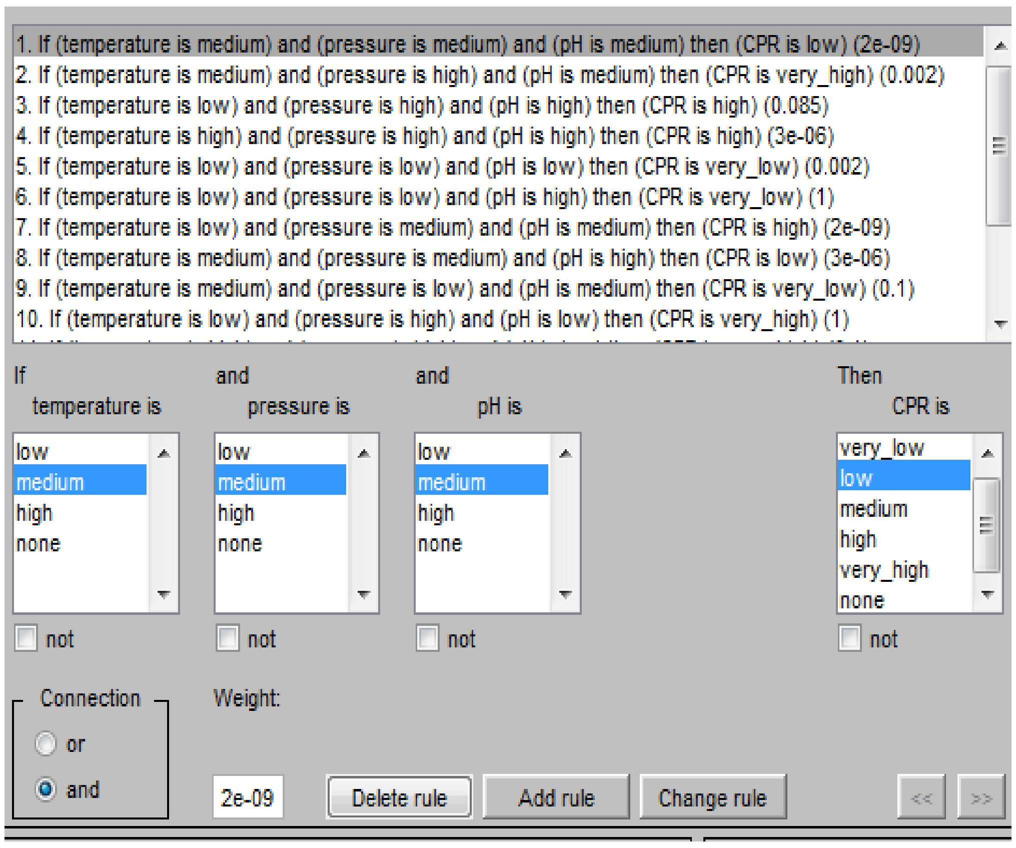

Figure 7: Fuzzy logic rules for CPR

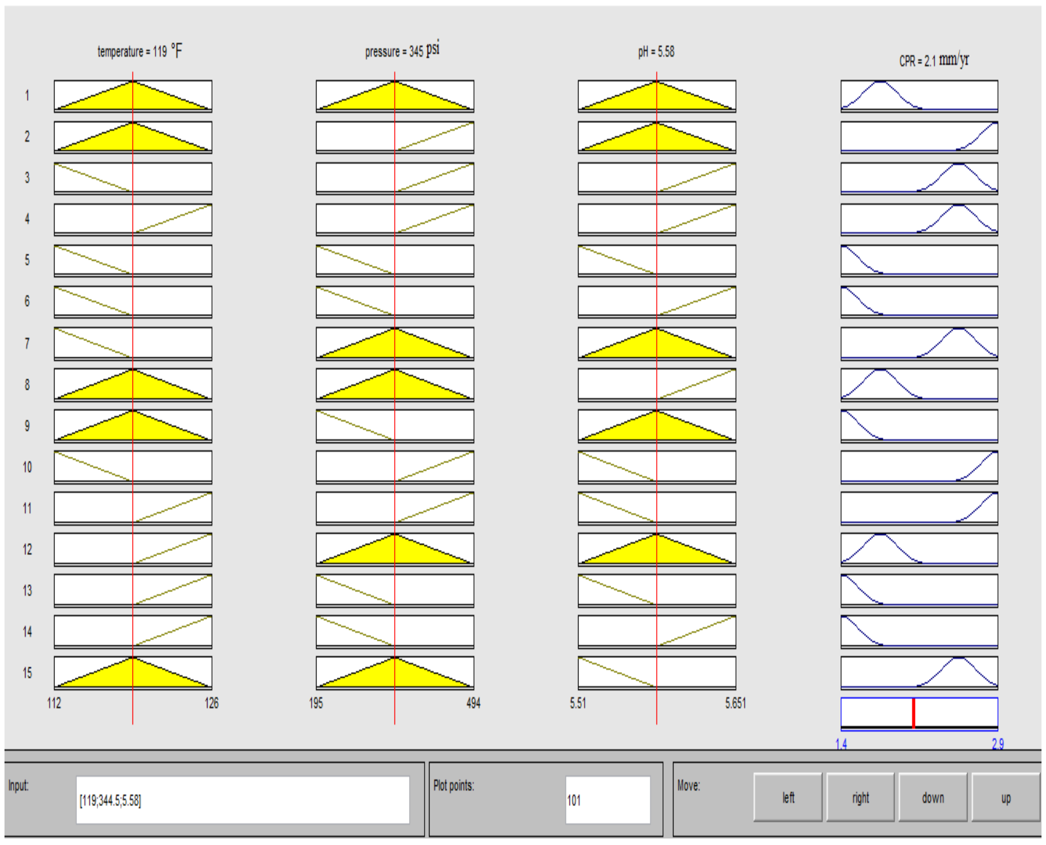

Figure 8: Fuzzy logic simulation stages

Table 5: The calculated, the predicted values of CPR and the mean absolute error

Run	Standard Order	Run Order	Point Type	Blocks	T (°F)		P (psi)	pH	Calculated CPR (mm/yr)	Predicted CPR (mm/yr)	Absolute Error
1	16	1	0	1	119		344.5	5.58	2.1	2.1	0
2	12	2	-1	1	119		494.0	5.58	2.6	2.6	0
3	7	3	1	1	112		494.0	5.65	2.5	2.5	0
4	8	4	1	1	126		494.0	5.65	2.3	2.3	0
5	1	5	1	1	112		195.0	5.51	1.7	1.7	0
6	5	6	1	1	112		195.0	5.65	1.5	1.5	0
7	9	7	-1	1	112		344.5	5.58	2.2	2.2	0
8	18	8	0	1	119		344.5	5.58	2.1	2.1	0
9	15	9	0	1	119		344.5	5.58	2.1	2.1	0
10	20	10	0	1	119		344.5	5.58	2.1	2.1	0
11	14	11	-1	1	119		344.5	5.65	2	2	0
12	11	12	-1	1	119		195.0	5.58	1.6	1.6	0
13	3	13	1	1	112		494.0	5.51	2.9	2.8	0.1
14	4	14	1	1	126		494.0	5.51	2.7	2.7	0
15	10	15	-1	1	126		344.5	5.58	2.1	2.1	0
16	2	16	1	1	126		195.0	5.51	1.6	1.6	0
17	6	17	1	1	126		195.0	5.65	1.4	1.5	0.1
18	13	18	-1	1	119		344.5	5.51	2.3	2.3	0
19	19	19	0	1	119		344.5	5.58	2.1	2.1	0
20	17	20	0	1	119		344.5	5.58	2.1	2.1	0
	Mean Absolute Error										0.01

CONCLUSION

The overriding purpose of this study was to implement the Fuzzy Logic technique to predict the CO_2 corrosion penetration rate of the Sarir-Tobruk pipe line used for crude oil transportation processes. From this study, the following points could be concluded:

- A fuzzy logic model was successfully introduced and used to predict the CO_2 corrosion penetration rate (CPR) within the range of the input parameters.
- The model was created based on design of experiments and on independently calculated data obtained using Norsok M-506 software. The model validation was performed using mean absolute error. This error was calculated to compare the fuzzy model predicted CO_2 corrosion penetration rate with that calculated using NORSOK M-506 software.
- The mean absolute error (MAE) was 0.01, indicating that fuzzy logic could be a useful prediction tool for engineers and operators dealing with the prediction of CO_2 corrosion created in crude oil pipe line transportation system.

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