Optimizing Crude Oil in Transportation Pipeline using Response Surface Methodology

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ABSTRACT

In this study, response surface methodology (RSM) has been employed to study, model and optimize the effect of some operation parameters of crude oil transportation processes, by pipeline, on the corrosion penetration rate (CPR). The parameters studied were, pressure, temperature, and pH, and their ranges were determined.

Response surface methodology (RSM) has been applied using Central Composite Design (CCD) to generate specific number of experiments to check the CPR, The predicted values obtained using developed model were compared with the actual values calculated using NORSOK M-506 standard software based on the mean absolute error (MAE).

Analysis of variance (ANOVA), surface and contour plots were applied for prediction, modelling using first and second order models and optimizing process parameters.

The value of the MAE was 0.047467 which indicated that, the model is reliable and significant. Moreover, the optimal values of the studied parameters, pressure, temperature, and pH achieved.

Keywords: Corrosion, Modelling, RSM, CPR, CO2, Prediction, Optimizing.

ÖZ

Bu çalışmada, boru hattı ile ham petrol taşıma süreçlerinin bazı çalışma parametrelerinin korozyon penetrasyon hızı (CPR) üzerindeki etkisini incelemek, modellemek ve optimize etmek için tepki yüzeyi metodolojisi (RSM) kullanılmıştır. İncelenen parametreler basınç, sıcaklık ve pH idi ve aralıkları belirlendi.

CPR'yi kontrol etmek için belirli sayıda deneyler üretmek için Merkezi Kompozit Tasarım (CCD) kullanılarak Yanıt Yüzey Metodolojisi (RSM) uygulanmıştır.

Geliştirile model kullanılarak elde edilen tahmin değerleri, NORSOK M-506 standart yaz -ılımı kullanılarak hesaplanan gerçek değerlerle karşılaştırılmıştır. Ortalama mutlak hata (MAE).

Tahmin, birinci ve ikinci mertebeden modeller kullanılarak modelleme ve süreç parametrelerinin optimizasyonu için varyans analizi (ANOVA), yüzey ve kontur çizimleri uygulanmıştır.

MAE değeri 0.047467 olup, modelin güvenilir ve anlamlı olduğunu belirtmiştir, Üstelik, incelenen parametrelerin, basınç, sıcaklk ve pH optimal değerleri elde edilmistir.

Anahtar Kelimeler: Korozyon, Modelleme, RSM, CPR, CO2, Tahmin, Optimizasyon.

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AE	Absolute Error
CCD	Central Composite Design
CO2	Carbon Dioxide
CPR	Corrosion Penetration Rate
DOE	Design Of Experiment
F°	Fahrenheit
H2S	Hydrogen Sulfide
KM	Kilo Meter
MAE	Mean Absolute Error
mm/y	Millimeters Per Year
NDT	non-destructive testing
P	Pressure
pH	Potential Of Hydrogen
PRESS	prediction errors sum of squares
Psi	Pounds Per Square Inch
RSM	Response Surface Method
Temp	Temperature

Chapter 1

INTRODUCTION

The maintenance and repair cost faced by crude oil transporters makes up huge part of their overall economic. The annual corrosion cost is estimated to be about $276 billion in the United States alone, which makes up about 2.5% of the US overall national product. An estimated $12 billion is related to oil and gas industry transportation lines [16].

Moreover, the biggest issue in oil and gas industry corrosion is CO2 gas; the hydration of CO2 to carbonic acid minimizes pH and causes corrosion on mild steel. Environmental conditions such as; CO2 partial pressure, flow conditioning, temperature and corrosion film properties all affect the degree of corrosion.

Corrosion is one of the biggest issues in the oil extracting industry. The use of carbon steel in oil pipelines and production in carbon dioxide (CO2) environments depends primarily on either the use of corrosion inhibitors or protective corrosion film products. The type of general of local and corrosion cracking depends on prevailing conditions and the complexity of the corrosion process of carbon steel containing CO2 [1].

The dimension for pipelines varies; it depends on the preference of the company and locations. The most common is the 30 inch diameter pipeline. The pipelines are used to transport oil and other associated products from the refinery to the consuming area. The pipelines are used to also transport products across countries at an international level. The crude oil is moved to the refinery where is refined into petroleum products.

1.1 Akakus Oil Operation Pipeline Profile

This is 30-inch export pipeline that covers a 722.8Km distance from (Shararra) NC-115 to Zawia. The south section from NC-115 to Hamada covers a distance of 339.8 km. The north section from Hamada to Zawia Terminal runs the remaining 383 km.

The lowest point in the south is located at KP208 which is 208 km from NC-115. The elevation of this point is +368.9 meters, which is 132.1 meters, lower than NC-115.

The highest point is located at the top of Great Jebel, an elevation of +698.6 meters. This is located 627.8 km from NC-115 and 95 km from Zawia Terminal (+13.27 meters)

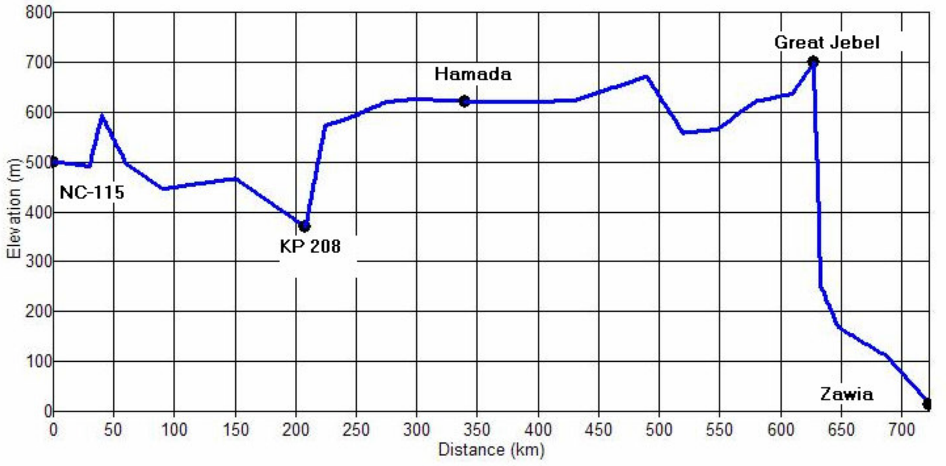


Figure 1.1: Pipeline Elevation Profile

1.2 Definition Of Corrosion

Electrochemical oxidation, commonly known as corrosion of metal is the reaction of oxidants such as oxygen or sulfur with metal. It is a natural process that coverts refined metals to a more stable form such as its oxides, hydroxides or sulfide. It involves the gradual destruction of materials by chemical reaction with their environment.

The corrosion of internal pipeline is primarily associated with the presence of free water, particularly its reaction with CO2, H2S and organic acids. To lower corrosion rate and oil-water interfacial tension, corrosion inhibitors are used. They are surface active chemicals that affect the oil-water flow pattern and the wettability of the steel surface [16].

The phenomenon "corrosion" can be described as a process that involves irreversible deterioration of substance properties as a result of reaction with its environment. There are different types of corrosion, but it is basically an interaction between two mechanisms. The common types of corrosion are: flow assisted corrosion caused by fluid flow, fretting caused by friction and rubbing, cracking caused by tensile stress, high temperature corrosion caused by alloy melting and electrochemical corrosion caused by electron transfer. In this thesis, we focus only on CO2 corrosion, which is a special form of electro chemical corrosion [1].

The main causes of internal corrosion are water, CO2 and H2S. They can be aggravated by microbiological activities in the pipeline. The transportation of crude oil through pipelines always comes with traces of water and some "acid gases" such as CO2 and H2S. Basically, corrosion problem in oil and gas pipeline is a combination of the following factors: carbon dioxide (CO2), and hydrogen sulfide (H2S), free water, suspended solids (sand), temperature, flow velocity and bacteria.

1.3 Corrosion Types

The types of corrosion are classified according to the materials causes of deterioration. Below are listed the nine common types of corrosion.

1.3.1 General Attack Corrosion

General attack corrosion also known as uniform attack corrosion is the most common type of corrosion. It is caused by chemical reaction or electrochemical reaction resulting to severe deterioration of the exposed metal surface. This reaction ultimately deteriorates the metal to the point of failure.

The general attack corrosion is considered to the cause of metal destruction by corrosion. However, it considered to be the safest form of corrosion because it is predictable and therefore manageable and preventable. Figure 1.2 shows a description of general attack corrosion.

Figure 1.2: General attack corrosion [28]

1.3.2 Localized Corrosion

Localized corrosion is a corrosion that targets a specific area of metal. There are three classifications of localized corrosion.

1.3.3 Pitting Corrosion

Pitting exist when a small hole or cavity forms in the metal as a result of the passivation of a small areal on the metal. The area becomes anodic, and remaining part of the metal becomes cathodic, thereby producing a localized galvanic reaction. The small area gets penetrates deeper and can lead to failure. The pitting corrosion is difficult to detect due to its nature and may be covered corrosion produced compounds. Figure 1.3 shows the pitting corrosion.

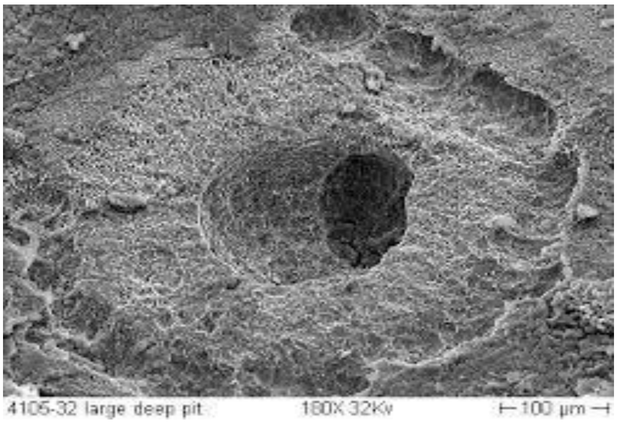


Figure 1.3: Pitting [28]

1.3.4 Crevice

The crevice corrosion occurs at a specific location like the pitting corrosion, it is often associated with a stagnant micro-environment similar to those found under washers, clamps and gaskets. Reduction of oxygen in a crevice or acidic conditions results to crevice corrosion as ca be seen in Figure 1.4

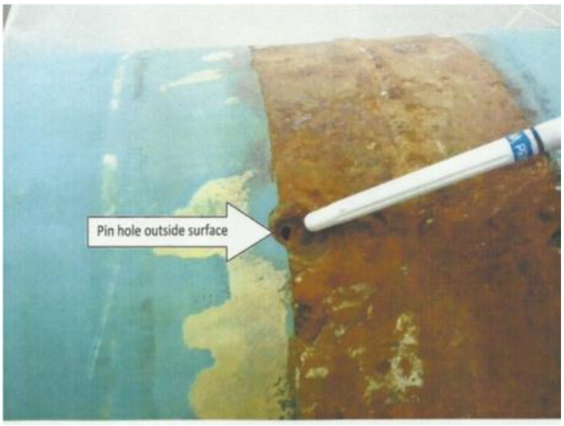


Figure 1.4: Crevice [28]

1.3.5 Corrosion Under Deposit

This is result of water breaching the coating surface under a paint or plated surface. It begins as a small defect in a coating and spreads, causing structural weakness as shown in Figure 1.5

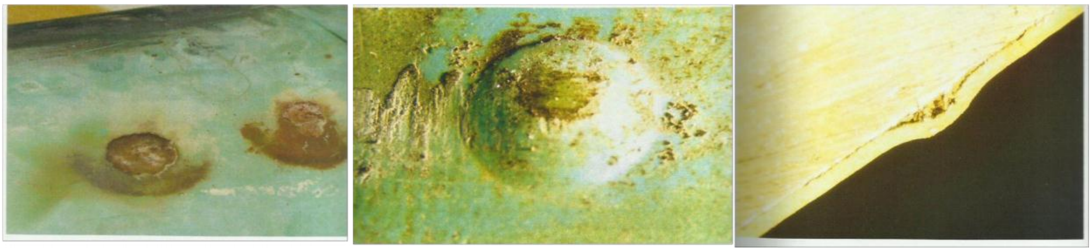


Figure 1.5: Corrosion under deposit [28]

1.3.6 Galvanic Corrosion

The corrosion otherwise known as dissimilar metal corrosion involves two distinct metals located together in a corrosive electrolyte. One becomes the anode and the other becomes the cathode together forming a galvanic couple of two metals. The sacrificial metal or anode deteriorates and corrodes faster than the cathode. Figure 1.6 shows the galvanic corrosion process.

Figure 1.6: Galvanic corrosion [28]

1.3.7 Environmental Cracking

This is a corrosion process that involves the combination of various environmental conditions. Figure 1.7 shows the environmental cracking corrosion process. Temperature, chemical and stress-related conditions can cause the following types of environmental corrosion:

- Stress Corrosion Cracking (SCC).
- Corrosion fatigue.
- Hydrogen-induced cracking.
- Liquid metal embrittlement.

Figure 1.7: Environmental cracking [28]

1.3.8 Flow-Assisted Corrosion (FAC)

Flow-assisted corrosion or flow accelerated corrosion is removal or dissolution of a protective layer of oxide on a metal surface by fluids such as wind or water, thereby exposing the underlying metal to extensive corrosive agent. Figure 1.8 shows the flow assisted corrosion.

Figure 1.8: Flow-assisted corrosion [28]

1.3.9 Intergranular Corrosion

Intergranular corrosion is an attack on the grain boundaries of a metal by electrochemical or chemical process. It occurs as a result of impurities in the metal that are usually concentrated close to the grain boundaries of the metal. The boundaries tend to be more vulnerable to corrosion than the rest of the metal. Figure 1.9 shows the intergranular corrosion

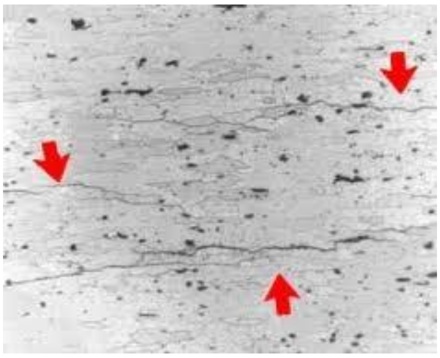


Figure 1.9: Intergranular corrosion [28]

1.3.10 De-Alloying

De-alloying or selective leaching is a corrosion process that targets specific elements in an alloy. De-zincification of unstabilized brass is the most common type of de-alloying. This results to the deterioration and porosity of copper.

1.3.11 Fretting Corrosion

Fretting corrosion occurs when there is excessive weight and/or vibration and wearing on an uneven, rough surface. These results to pits and grooves on the surface.

Fretting corrosion is mostly found on impact machinery or rotation surfaces, bolted assemblies and bearings. They are also common on surfaces exposed to vibration during transportation.

1.3.12 High-Temperature Corrosion

This is caused by the formation of compounds with a low melting point during combustion of fuels used in diesel engines, gas turbines and other machineries are very corrosive towards alloy metals which are resistant to high temperature and stainless steel. The fuels contain vanadium or sulfate that exacerbates the process.

Other cause of high temperature corrosion includes high temperature oxidation, carbonization and sulfidation. Figure 1.10 shows the high temperature corrosion process [54].

Figure 1.10: High-Temperature Corrosion [28]

1.4 Corrosion Prediction

Selecting materials for in the design stage of construction requires prediction of corrosion behavior to give operational integrity to the project. Many industries have developed CO_2 corrosion prediction models to help improve their predictions. Such models provide accurate predictions. However, they are valid only in some specific conditions. The results obtained from a single case might vary, therefore understanding the basis of the developed model is required to interpret the results meaningfully. The interpretation of CO_2 corrosion is well documented and accepted, however its combination with other species such as HAc is yet to be generally accepted. The problem becomes more complicated as the process is further influenced by not only the reservoir type but also other operational parameters within the process such as pH, temperature and flow condition. The interaction of different species and operational conditions further complicates the corrosion predication process. The precision and accuracy of the corrosion model is heavily dependent on the approach the prediction model uses to treat the variables effects on the process.

Many CO_2 corrosion prediction research have been published on the effects of species HAc with several other operating parameters including temperature, pH, and flow rate condition had been published[2],[36],[37]. Most of which rely specifically on algorithms to combine the individual effects of the species to give a representation of the expected total corrosion rate. The individual effects are derived from experiments by holding certain variables constant and alternating the values of other variables. This is considered an inefficient approach because large number of experiments ae needed to process all possible corrosion data. In addition, it does not simultaneously cover the represented data.

1.5 Motivation And Structure Of The Project

The “find it and fix it” approach to corrosion maintenance has been the most common practice for decades in Libya flow lines. The rest of the world is transitioning into a more efficient and reliable maintenance approach. Therefore, Libya must replace its approach by an approach that has the ability to predict and monitor corrosion process using fundamental parameters to understand the process.

This thesis builds a CO_2 corrosion model to predict corrosion rate by optimizing crude oil in transportation process using response surface methodology (RSM) and NORSOK m-506 software. There are models available in the open literature or as commercial products. We focus on improving the existing models by determining the optimal process parameters as oppose to reproducing the existing results. To achieve this goal, the project consists of six chapters. Chapter one presents an introduction. Followed by chapter two literature reviews. Chapter three describes the response surface methodology and NORSOK standards. Chapter four presents the methodology. Chapter five present an implementation of the response surface method, results and discussion. Chapter six presents a conclusions and recommendations of the thesis.

Chapter 2

LITRATURE REVIEW

The transportation of crude oil through pipe lines is an important part of moving crude oil from drilling platforms to refineries. The composition and chemical reactions that occur during transportation is an irreversible and uncompromised part of the transportation process. The chemical reactions sometimes create problems during the refining process of crude oil. Aside the refining problems, the transportation rate can also be affected by the transportation problem. Optimizing crude oil transportation has manufacturing, operational and financial benefits. [2] Stated that an annual estimated cost of all forms of corrosion to the Oil and Gas sector was $13.4 Billion. This study tries to optimize the transportation of crude oil by considering important parameters such a temperature, pressure and PH levels. Using response surface methodology (RSM) and model, procedures will be proposed to optimize the transportation of crude oil. Various researches have been published on the optimization of crude oil transportation using the mentioned parameters. All the above mentioned parameters play an important role in the transportation of crude oil.

Corrosion is the retrogression of materials, mostly metals as a result of reaction between the material and environment [2]. A survey carried out by US Minerals Management Services in the case of petroleum pipeline corrosion problems states that the problem is due to internal corrosion than external corrosion. The internal corrosion is a result of result of reaction between the material that is transported and the pipe. In France, it was estimated that 8.5% of the leakages were cause by internal corrosion. Several factors contribute to the reaction between the material and the pipe used in the transportation. Pitting corrosion

There are different types of corrosion detected in the transportation of crude oil. They all impose different types of constraint in the transportation of the products. The common types of corrosion are a) Uniform\ general corrosion\ metal loss b) cavitation c) pitting corrosion d) stay current corrosion e) microbiologically-influenced (MIC) f) Erosion corrosion. They are all peculiar in nature but are all cause by similar factors. Figure 2.1 shows the types of corrosion on pipelines [51]

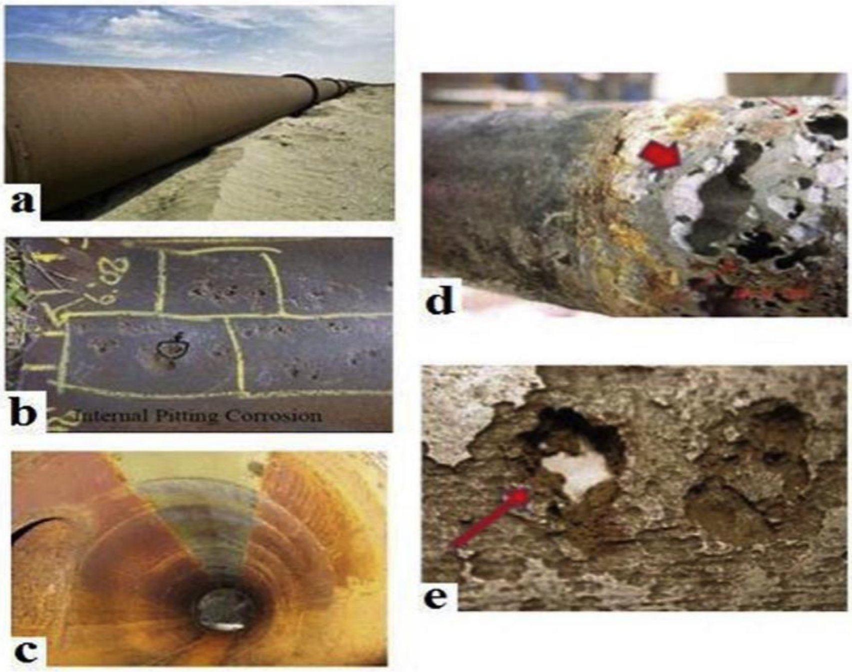


Figure 2.1: Oil and Gas common forms of corrosion [47]

Corrosion in pipeline is affected by temperature, CO2 partial pressure, flow velocity, PH and water cut. Research on the effect of the respective factors on corrosion rate is improving enormously. It is a general belief that: an increase in CO2 partial pressure increases corrosion rate, because when partial pressure increases, solubility of H2Co3 which is the corrosive medium increases, leading to decrease in pH value of the corrosive solution causing depolarization reaction thus accelerating the corrosion rate [60]. The protective film of the pipe is affected by the temperature variation. Temperature acceleration can accelerate the deposition of corrosion product film and accelerate the reaction rate [14]. An increase in flow velocity can led to an increase in corrosion rate. Primarily because the flow rate will speed up towards and away from the surface of the pipeline material [55]. Water cut has significant impact on corrosion rate. An increase in water cut causes increase in corrosion rate [56].

Temperature is an important parameter that is critical to pipe corrosion such as physical properties of the solution, biological activities, chemical rates, physical properties of corrosion scale and thermodynamics. The variation in temperature itself and the temperature gradient gives room for more corrosion phenomenon. [34] Highlighted the importance of temperature in assessing pipe corrosion. Pipes in a distribution system are always submersed, either in the soil or water for the transportation of crude oil. That depends on the initial location of the drilling platform. The surrounding temperature of the submersed pipe (soil of water) is relatively constant. However, the temperature within the pipe can change due to seasonal variation [34]. This may cause pipes to exhibit different corrosion behavior over different season. Figure 2.2 shows the possible effects of variation in pipe constant temperature.

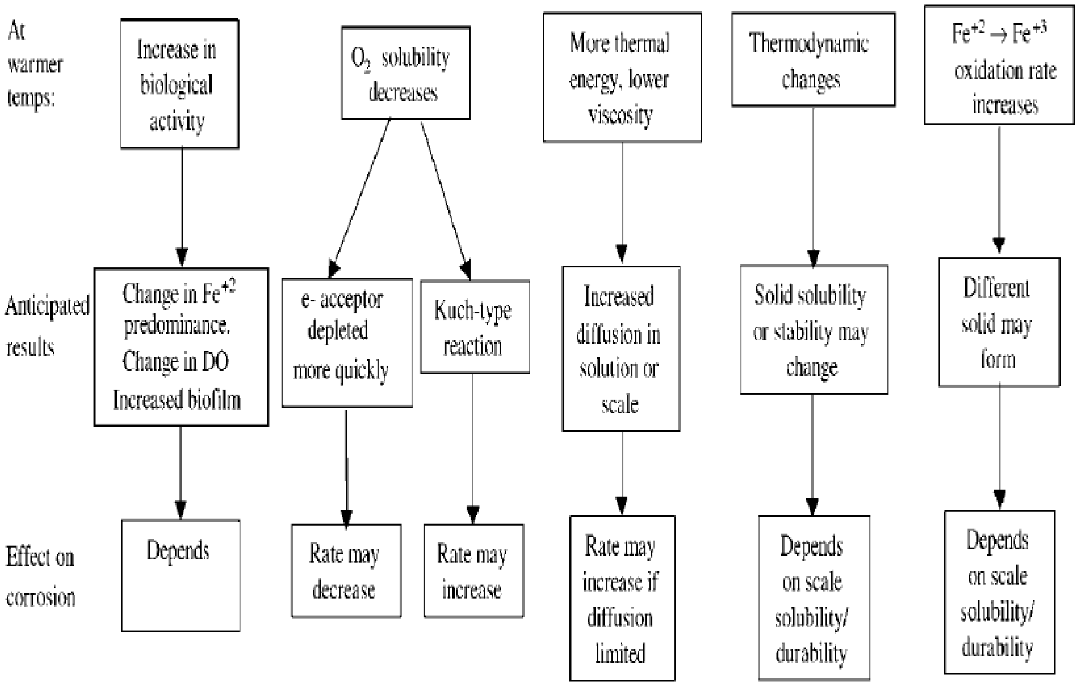


Figure 2.2: possible effects of variation in constant temperature [34]

Viscosity, which is an important property in crude oil, is a very important parameter that can lead to corrosion as a result of temperature difference. The temperature affects the flow of crude oil, especially extra heavy and heavy crude oil. The transportation of crude oil, especially heavy oil needs a stable viscosity. In most cases reducing the viscosity is more prevalent. A common way of reducing viscosity is the dilution process which has been in use since 1930's. Recently, [50] proposed a combined dilution method to deal with issue of viscosity in the transportation of crude oil. Formation of emulsion in the crude oil is a phenomenon associated to viscosity. They normally occur in petroleum production pipelines. Such emulsions are highly detrimental for oil production since the viscosity of the oil rises. Figure 2.3 shows the emulsions that naturally occur in pipelining for water-in-oil (W/O) and a more complex emulsion like oil-in-water-in-oil (O/W/O).

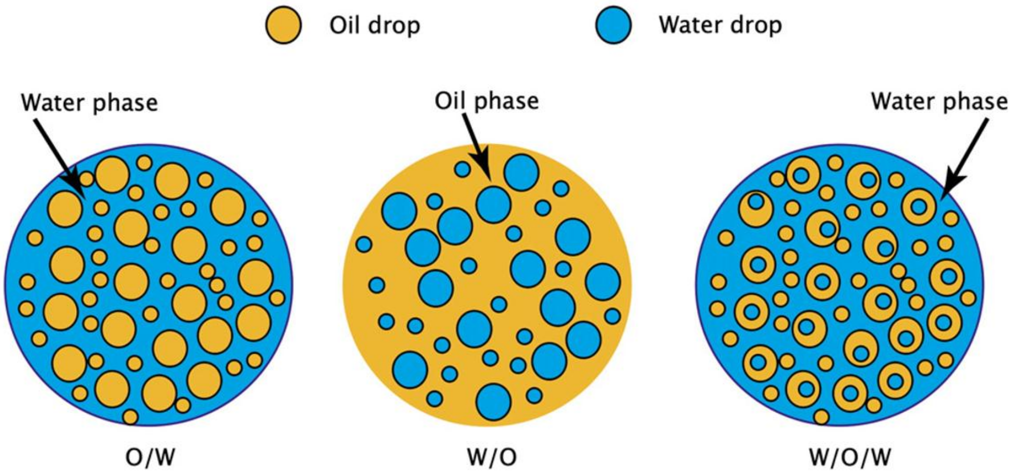


Figure 2.3: c. [33]

The second most popular method for transporting crude oil is the heated pipelines. The principle in application here is to conserve the elated temperature as a result of temperature to (<373.15K). External heating of the pipeline might be needed as a result of heat loss [33].

Thermodynamics properties of crude oil such as activity coefficient, enthalpy of reaction and solubility are all properties that are influenced by temperature. Temperature variation which is different from average temperature change can be experience in the temperature gradient over a short period. This might happen due to changes in solar intensity or distribution. Studies such as [46] have shown that temperature distribution system can vary seasonally. Variation in temperature has significant effects on corrosion. Figure 2.4 shows possible effects that can result from temperature variation on iron corrosion.

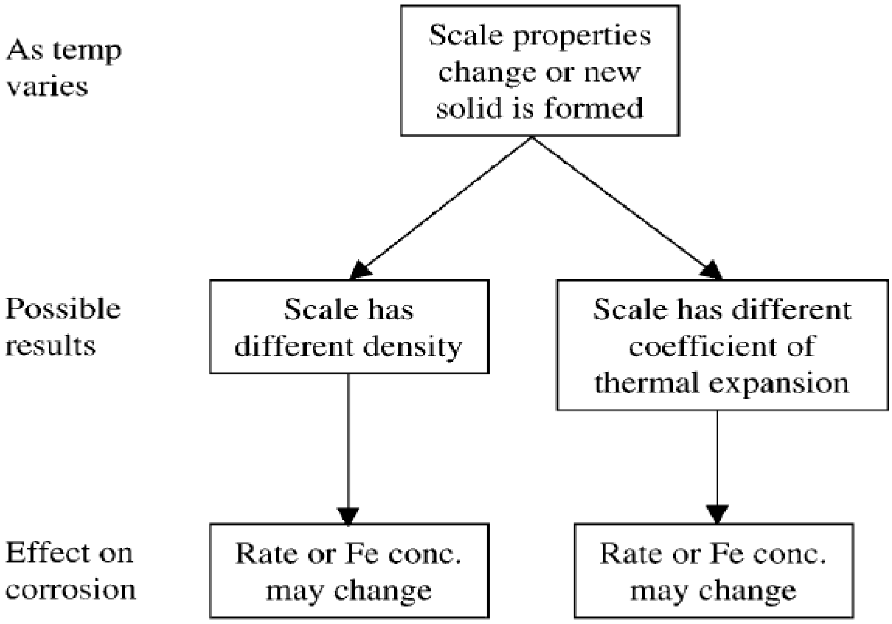


Figure 2.4: effects of varying temperature on corrosion [34]

The problem of pressure in the transportation of crude oil is a problem associated to the speed of flow of the crude oil. Reducing friction is a method of improving the pressure of crude oil flow. [33] Explained reducing friction by drag reducing additives, highlighting that the force that must be overcome during transportation of fluids in pipelines is the drag force of simply drag. This is as a result of the stresses at the walls resulting to a drop in fluid pressure. To achieve the desired throughput, the fluid must be transported with adequate amount of pressure to overcome this force. To maintain the flow at the same average velocity, some pressure must be applied. Pressure associated problems occur frequently when transporting crude oil over a long distance, which is seldom the case. Temperature is also associated to the pressure of the fluid, because if the temperature is low, the pressure also drops which affects the flow and corrosion of the pipelines. Drag reducing agent can also be used to improve the pressure of the crude oil flow. Polymer film formation inside the crude oil matrix is also suggested to lubricate it and allow an effective drag force reduction [48]. An important requirement is for the drag reducing additive added into the crude oil to minimize the drag force to be soluble in the crude oil [33]. To reduce the drag force, [35] proposed the application of an annular ring with inexpensive micellar solution to form temporary film in the interior part of the pipeline. This system contains surfactants, hydro carbons and water maintained in the pipeline by continues injection to be absorbed by the crude oil transported. This especially way is especially useful in transportation in commercial pipelines with high viscosity, because such fluids require drag reducing films. Old pipelines exposed to crude oil are generally oil-wet, therefore oil-external micellar solution be can sucked to the surface of the pipeline. [57] Developed a solution by pacing a spherical sealed pig within the pipeline at a desired position, filling the pig with low viscous fluid such as water, transporting the core with the intended crude oil. To restart the flow after a long stand still period, [58] proposed a method by first pumping a low viscous fluid like water on the portion of the pipeline until it reaches critical velocity. Then flow the heavy oil into the inlet pipeline adjusting the control value by a bypass line. Figure 2.5 shows the pipeline design used to overcome heavy oils after stand still period designed by [58].

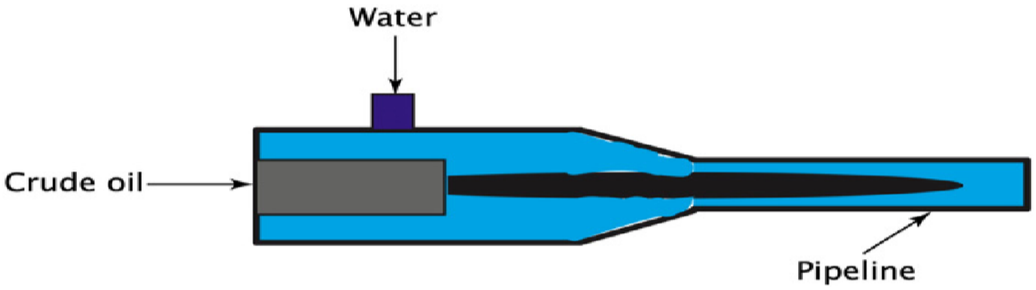


Figure 2.5: Pipeline design scheme for core flow of heavy oil after stand still period [58]

Developing anti corrosion methods for the transportation of crude oil has been the focus of researches recently in the oil and gas industry. The methods developed are either calculated in advance or performed as part of the maintenance process of the transportation system. Number of methods have been published, some of focuses on the simulation of C02/oil/water emulsion using weight loss technique, characterization of the corroded surface technique and potentiondynamic polarization technique. The common process of the techniques is testing the effects of temperature, partial pressure and velocity on the CO2 corrosion of the pipeline system. Some studies such as [10] shows that water cut is the primary controlling factor of corrosion. Mainly in the APIX65 steel corrosion under the CO2/oil/water conditions with significant impact on morphology. Different rates of pipeline corrosion in two crude oil production pipes using metabolonic and metagenomic analysis was studied by [7]. Their analysis focuses on the corrosion process in two North Sea oil pipelines. Early and late pigging materials were extracted to gain insight into the potential triggers of different corrosion rates. Using ultra-high performance liquid chromatography to analyze the extract, they predicted masses from KEGG metanolites.

Chemical compounds such as naphthenic acids and sulfur compounds found in crude oil may cause corrosion in oil refineries. These are some factors that must be considered during the planning process of corrosion mitigation in crude oil transport and processing. Corrosion protection may be found in some oil products, but it may not be true in some cases. Using microscopic and analytic techniques, the nature of protective scale found on the corroded steel by the crude oil fractions was studied by [19]. They identified a thin oxygen-containing layer just between the steel and thicker outer layer of iron sulfide contributing to the protection against naphthenic corrosion acid.

Measuring key parameters of corrosion penetration rate (CPR) of crude oil transportation process such as pressure, temperature and PH is needed to optimize crude oil transportation. Research has shown that “find it and fix it” approach for mitigating corrosion has less effect and enormous financial burden for the oil companies especially in Libya. Technologies are continuously been developed to monitor and mitigate corrosion in crude oil transportation in pipelines. The traditional method for monitoring corrosion is the manual non-destructive testing (NDT) methods. Recent advancement includes the deployment of cellular-based ultrasonic corrosion measurement system. This technology has improved in precision, cellular data back-haul to improve accuracy, coupled with fully-digital wall-thickness measurement system. Stationary mechanical integrity programs have recently been complimented with remote ultrasonic thickness monitoring devices [6]. This technology can provide snapshot of the particular conditions of the pipelines and its location. This system supplements the constant inspection of pipelines for corrosion rate, and provides data for more informed decision about the state of the pipeline [6]. It helps locate corrosion. Resources can be optimized and the overall risk of unexpected failure is decreased. The use of ultrasonic principle is applied. Figure 2.6 shows the instrument which is installed in the pipelines for measurement. It collects ultrasonic and other relevant data associated to the conditions of the pipeline. It then sends and stores it to the browser. Figure 2.7 shows an interface of the data set sent by the sensor showing the present corrosion condition of the pipelines. A major advantage of this technology is its ability to collect large quantity of data concerning the corrosion state of the pipeline for analysis. The dynamics of the wall thickness reduction, corrosion rate at every period is observed.

Figure 2.6: Ultrasonic installed sensor system on pipelines [6]

☐ Obsolete	Measurement Timestamp	Calculated Thickness (in)	Temp Comp Thickness (in)	Material Temperature (°F)	Corrosion Rate Short (in/yr)	Corrosion Rate Long (in/yr)
☐	Dec. 7, 2016, 6 p.m.	0.125	N/A	57.4	0.048	0.003

Figure 2.7: Interface of ultrasonic monitoring of an overhead crude line [6]

Since the "find it and fix it" approach of mitigating corrosion is not promising models for predicting and monitoring the behavior of corrosion growth is more applicable. Literature has shown that various models have been proposed to predict the behavior and growth of corrosion in pipelines. The models proposed are mostly categorized into deterministic and probabilistic models. The deterministic models include single-value corrosion growth (SVCR) model, linear corrosion growth rate model and non-linear corrosion growth rate model. The probabilistic models include Gamma process, the BMWD model, markov model, monte-carlo simulation, time independent GEVD model (TI-GEVD) and time dependent GEVD model (TD-GEVD). The single value corrosion growth approach is a special and limited case if linear programming growth rate model in which the growth rate is independent of age and corrosion depth defects. Linear growth rate model estimate corrosion depth defect over time by assuming corrosion growth rate behavior is linear. The corrosion rate distribution estimated by the non-linear corrosion growth rate model is used in underground pipelines. Which is based on the operator’s knowledge of soil and pipe materials? When uncertainties can happen in the corrosion rate prediction, probability becomes a possible scenario and must be factored in the statistical method. Gamma distribution is similar to Gaussian distribution. An assumption in using the gamma distribution is that the defects detectable by the ILI tool are assumed [33]. Figure 2.8 shows the distribution of the internal corrosion puts on heavy oil pipeline simulated using gamma function.

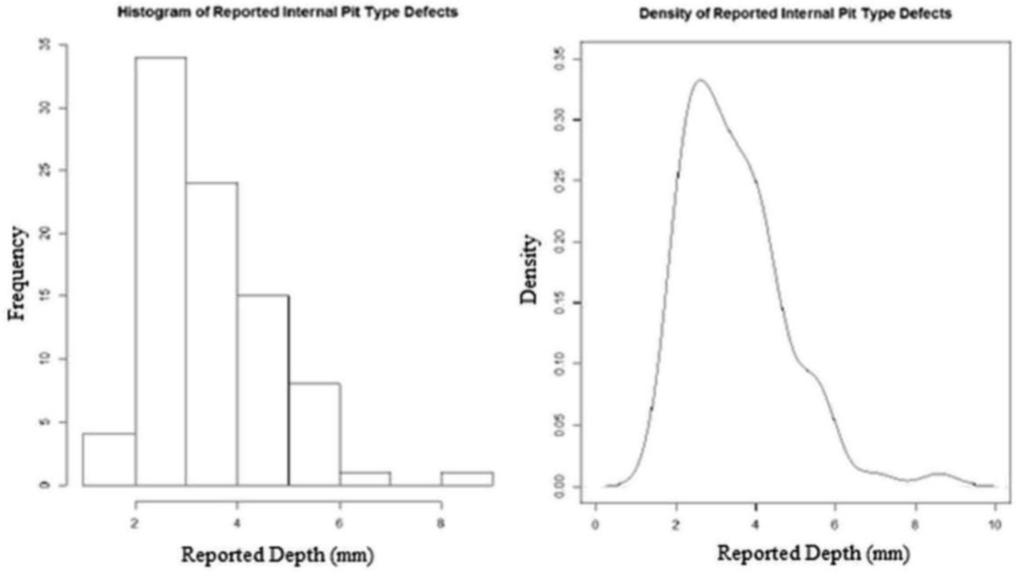


Figure 2.8: Heavy Crude oil pipeline pitting type defects distribution [33]

Response surface methodology (RSM): The building of empirical model through the collection of statistical and mathematical techniques is known as RSM (Patel & Patel). The aim is to optimize response (output variable) using several independent variables (input variable) that influence the output variable by carefully designing of experiment. [8] First introduced the RSM to model experimental responses; it was then modified to model numerical experiments. In the RSM, the errors are considered to be random. In using the RSM, the choices of design is dependent on the properties desired. Some common design properties is used in RSM are orthogonality, uniform precision, ratability, design robustness and design optimality [23].

The response surface methodology has been applied in various fields to optimize a certain process. It has been applied to optimize the effects of certain catalyst, calcination of roman cement. Find the adequate amount of preservatives and other important parameters. In this thesis, we are using the RSM to optimize the crude oil transportation. In the application of RSM, certain variables are tested at different levels to either maximize or minimize an output. The response can be represented in graphical form using three-dimensional space or contour plots to help visualize the shape of the response surface. Figure 2.14 shows a diagram of a three-dimensional response surface with its corresponding contour plots in an experiment of optimizing roman cement using calcination temperature and residence time to test the strength of the roman cement.

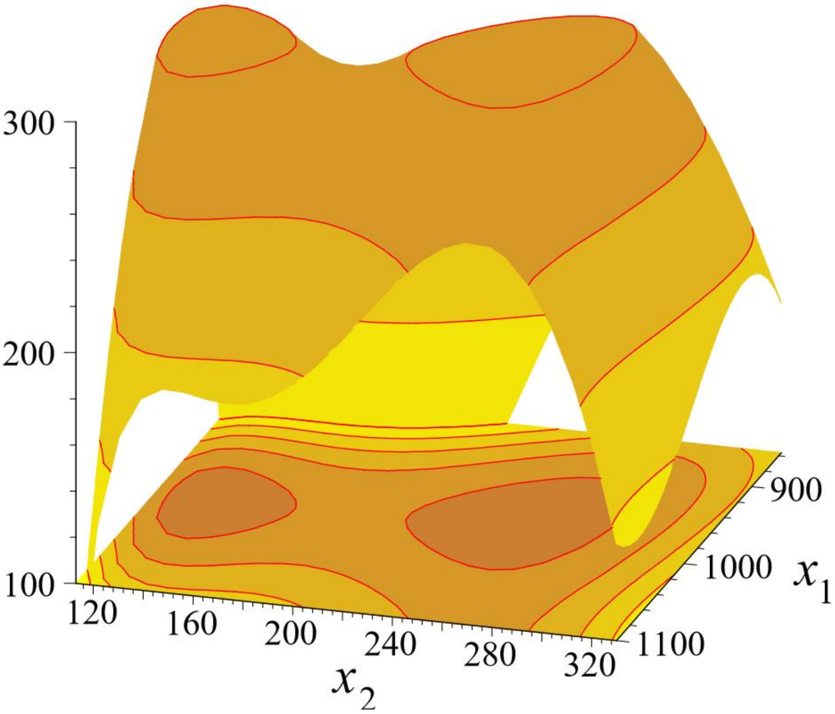


Figure 2.9: Three-dimensional graph of response surface methodology with two variables [23]

The response surface methodology is also used in prediction of certain parameters. In this thesis, the corrosion rate of materials for transportation of crude oil will be investigated using the RSM. Reviewing the literature on the applications of RSM to predict certain parameters: [36] used the RSM to predict biodiesel yield during transesterification. They examined the production of biodiesel from vegetable palm oil catalyzed by calcium oxide and modified by titanium dioxide. Catalyst dosage, volume of methanol and reaction time are independent variables and biodiesel yield is the dependent variable. Using RSM, the effect of the amount of PH and contact time on high-dose phosphate inhibitors on copper corrosion was evaluated by [18]. The box-behnken design model was used to obtain optimum operating condition to reduce cooper corrosion by applying high dose polyphosphate inhibition, using the response surface methodology, the main interactions between the parameters were investigated and highlighted. Using central composite design (CCD) and response surface methodology, co-solvent mixture and reaction conditions were optimized by [54]. The effects of three independent variables were examined. They are: reaction temperature, mass ratio and reaction time.

Extracting heavy-oil from reservoirs is a critical issue according to a survey in oil and gas journals, due to its high viscosity. Enhanced oil recovery (EPR) techniques has been the most widely used method in heavy oil fields in the US and Canada, but has not been successful in other parts of the world. Thermal methods like the steam injection are limited due to thin formation, reservoir depth and overlaying permafrost. To increase the net present value NPV of the project, an optimization procedure is performed in the post-evaluation stage of the project using the response surface methodology. The effects of different parameters on the removal of hex lent chromium using electrocoagulation with stainless steel electrodes by response surface methodology were studied by [43]. For the optimization of electrodes, central composite design was used. An optimal condition for complete 100% removal of hex lent chromium was established. This shows the extent in which the response surface methodology can be applied in determining optimal condition for removal or prevention of corrosion in pipelines. Kenaf seed oil is that has been considered edible but comes with some sort of odor as most oil does. These odors can be removed using chemical processes during refining. [11]applied the response surface methodology to optimize the deodorization parameters in chemical refining. The parameters studied were the effects of temperature and time in the deodorization stage of the refining process. Response surface methodology was used for parameter optimization in the extraction of essential oil from Artemisia annual L through superficial carbon dioxide by [26]. Their research shows that response surface methodology is an effective tool to predict optimal values of the extraction parameter. Their result produces a crude oil yield of 11.7%. Using the response surface methodology equation, the contribution of chemical dispersants and bio surfactants used in biodegradation of crude oil was studied by [45]. Their study evaluated the negative effects of crude oil degradation carried out in marine offshore oil spill. Optimizing the stability of Asphalthee particles in crude oil using response surface methodology was performed by [37]. They modelled and optimized the inhibition of asphalthene flocculation process. A study of [31] on the corrosion properties of manganese on AISI 410 alloy was investigated using electrochemical independence spectroscopy method. To measure the variables that influence the corrosion properties, Box-Behnken experimental design and response surface methodology was employed. The variables considered are the amount of packed concentration mixture of manganese, temperature and the amount of ammonium chloride. The study shows that Box-benken experimental design and response surface methodology can be applied for modelling diffusion coating properties for corrosion. The Co2 corrosion prediction model in pipe flow under FeCo3 scale formation conditions was proposed by [12].The model is capable of determining Co2 corrosion rate of carbon steel with conditions of Co2 partial pressure, solution chemistry, temperature, velocity and gas/liquid ratio that are desirable by the oil and gas industry. As a result of the protective nature of the scale, the corrosion rate can be very low. At different temperatures, the corrosion behavior of X65 pipeline steel at different temperature for various immersion times at low Co2 partial pressure and at supercritical condition of Co2 was investigated by [59]. They compared the Co2 corrosion products changes scale formed at different conditions with variation made of corrosion rate and temperature.

The development of mechanistic models and empirical models for the prediction of Co2 corrosion rate for application in oil and gas production system is growing. They all have different standards. [53] Compared Co2 prediction of different models. The input used in the model was water chemistry or condensed water, and the output considered for each of the Co2 prediction model was compared over different temperatures and pressures. They also considered the ease of implanting the prediction models in their assessment. Their conclusion was that the mechanistic models are more complex to implement. However, they offer the advantage of greater insight in to the variables during overall corrosion.

The literature showed above generally shows the use of response surface methodology in optimizing parameters in different fields including crude oil transportation. However, the results produced are experimental. In this thesis we will use the NORSOK program to determine the penetration rate of the experimental results produced by the response surface methodology. The NORSOK corrosion rate calculation model is a computer program used to calculate corrosion rate in hydrocarbon production and process systems were the corrosive agent is Co2. There have been various versions of the program, but the latest was published in June 2016[1]. The NORSOK program has been used in literature by numerous researchers to prediction corrosion rate and corrosion depth in pipelines.

For proper use of the NORSOK program, [41] stated the guidelines and limitations for the use of NORSOK M-506 model for corrosion prediction. In applying the NORSOK M-506 model, some basic principles must be adhered to/ it is an empirical

---

[1] NORSOK PROGRAM DEVELOPERS https://www.standard.no/en/nyheter/nyhetsarkiv/petroleum/2016/norsok-m-506--co2-corrosion-rate-calculation-model-on-public-enquiry/#.WWTHitSGPcs

model based on experiments under single phase loop. [42] Presented a basic principle in the application of the NORSOK M-506 Co2 corrosion prediction model. [20] Applied mathematical modelling of uniform corrosion based on corrosion rate prediction models available. They estimated corrosion rate of pipelines. In testing the effects of Bicarbonate, temperature and monoethylene glycol (MEG) concentrations on CO2 corrosion of carbon steel, [15]. In a condition where FeCO3 is spares, the Co2 corrosion of two mild steel was studied using a function of MEG and bicarbonate concentrate. The NORSOK program was applied to study the corrosion rate on the two mild steel. [30] Proposed a CO2 corrosion multiphase flow model that account for highly important variables, they employ a semi-empirical approach. Their model was a decade long project based on building from previous established literature. Their model was made up of two main models: the corrosion model and the multiple flow models. The model covers the following sub-models: H2Co3 deduction, Fe Oxidation growth of Iron, Carbon Films, effects of steel type, effects of inhibition by crude oil/or corrosion inhibitors etc.

[38] Combined the standards NORSOK Co2 prediction model and pipelines thermal/hydraulic calculation models to simulate the corrosion rate along pipelines. The affected factors along the pipelines at any condition were determined. The operational parameters of the pipelines were considered as input data and the results were analyzed at three flow velocities. The results show s that velocity affects the variation of thermal/hydraulics characteristics which consequently affects corrosion rate along the pipelines. When the velocity is low, temperature declines rapidly to the surrounding temperature and remains constant until the terminal point, when the velocity is high; the temperature most probably stays above the surrounding

temperature. Their results shows that corrosion rate decreases along the pipeline, which contradicts publishes filed data but necessary explanation were made.

Internal corrosion of wet gas gathering pipelines using a numerical corrosion rate prediction model was studied by [27]. They introduced a numerical internal corrosion rate prediction model into the internal corrosion direct assessment (ICDA) process for wet gas gathering pipelines based on generic algorithm (GA), back propagation (BP), particulate swarm optimization and BP artificial neural networks (ANNs). The corrosion rate was then calculated by NORSOK model. An extension of the NORSOK Co2 corrosion prediction model for elbow geometry was presented by [39]. The standard NORSOK model is applicable for straight pipelines for the transportation of oil and gas products, they modified the NORSOK model to enable it to be applicable for elbow geometry. Using the equivalent length concept, the modification was made. They presented a graphical friendly user interface for the computational package for the prediction of corrosion in both straight and elbow pipelines. Figure 2.15 shows the corrosion rate measurement in elbows.

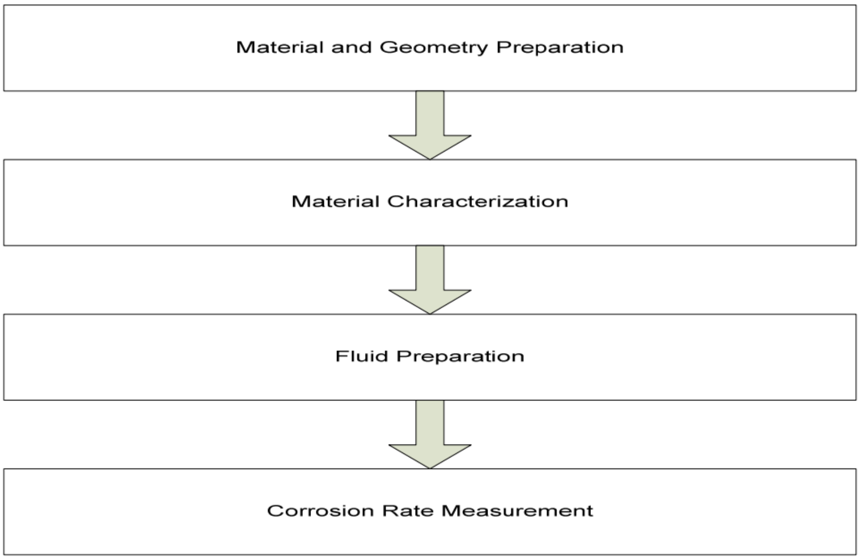


Fig 2.10: Corrosion rate experimental procedures measurement in Elbows [39]

[49] Investigated localized Co2 corrosion steel in wet gas services in both experimental and theoretical context. Under stratified annular flow conditions, multiple corrosion monitoring techniques was uses during the experiments. The post –test analysis involve a systematic investigation using parametric study to further investigate the effects of Co2 partial pressure, temperature, Cl, pH and flow regimes on the formation of corrosion film. Their results show that localized corrosion occurs at high temperature about (90 degrees) in both Cl^- and Cl^+ protection films.

In summary, sever degradation is mostly observed in carbon-steel pipes usually in offshore facilities. This degradation is of severe financial cost to the oil and gas industry. Research is heavily carried out in the area of predicting, optimizing and mitigating the parameters that causes Co2 corrosion in pipelines. Chemical processes are been employed to mitigate this corrosion as highlighted in the above literature review. However, it is agreed that at optimum conditions of the pipelines, Co2 corrosion can be reduced significantly or mitigated entirely. This attempt to predict the corrosion before it happens to prevent failure in the pipelines. Recently, [5] did an empirical prediction for carbon-steel degradation rate. Their study focused on offshore oil and gas facility by predicting Co2 erosion-corrosion in pipelines before failure occurs.

Chapter 3

RESPONSE SURFACE METHODOLOGY AND NORSOK STANDARDS

3.1 Response Surface Methodology

3.1.1 Introduction To (RSM)

Response surface methodology (RSM) is an optimization method that involves collection of mathematical and statistical techniques for building an empirical model. Using careful design of experiments, they aim to optimize a response (output variable) that is influenced by independent variables (inputs variables). An experiment is a series of tests that involves changing the input variables to monitor and identify its effects on the output response.

The initial development of RSM was to model experimental responses [8] it was then integrated to model numerical experiments. The major difference was in the type of error generated by the response. The physical experiments show inaccuracy as a result of measurement errors, while in computer experiments, numerical noise shows incomplete convergence of the iterative processes, round-off errors or the discrete representation of continuous physical phenomena [8]. The errors are assumed to be random in RSM. The aim of applying RSM is to reduce the cost of running expensive experimental analysis (e.g. finite element method or CFD analysis) and their numerical noises. The problem can be approximated using smooth functions to improve the convergence of the optimization process because they allow the use of derivative based algorithms by reducing the effects of noise. [23] Discussed the advantages of RSM in design optimization applications.

3.1.2 Response Surface Designs

The RSM is a design of experiment (DOE) method used for approximating an unknown function where only a few values are computed. The RSM was developed from science disciplines in which physical experiments are carried out to study unknown relations between a set of variables and the system response or output. Only a few experiments values are required. These relations are then modeled using a mathematical model, called response surface.

In some situations, quality engineers encounter several correlated responses simultaneously. In such cases, the decision on the optimal set of parameters becomes a mathematically complicated problem.

The prediction errors sum of squares (PRESS) and the residual method are the proposed models that have the capability of evaluating the designed models. Researchers could adhere to standard optimization techniques such as operations research and differentiation methods to set their process optimum conditions.

Graphical visuals are made for the response surface. The graph shows the shape of the response surface, highlighting the valleys, hills, and ridge lines. Hence, the function f (x1, x2) can be plotted versus the levels of x1 and x2 as shown as Figure 3.1. [56]

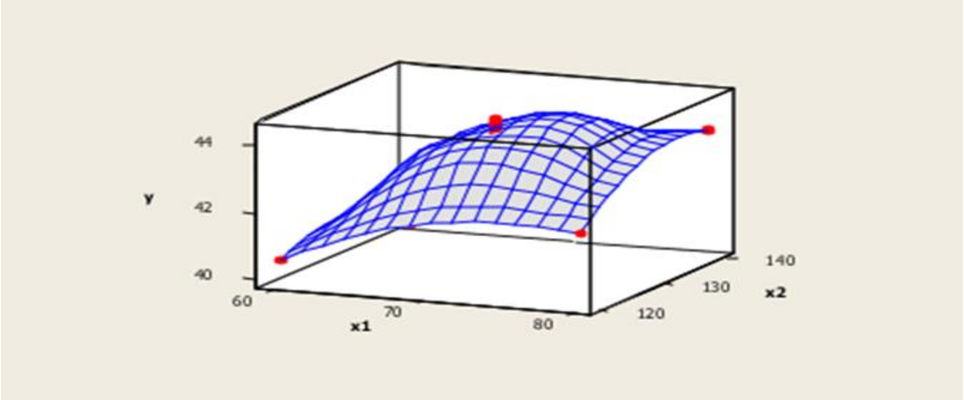


Figure 3.1: Response Surface Plot [56]

From the response surface graph, each values of x1 and x2 generates a y-value. The three-dimensional graph view from the side is called the response surface plot. Occasionally the two-dimensional view of the response surface is less complicated, the contour plots can show the contour lines of x1 and x2 pairs having response y more elaborately. Figure 3.2: shows an example of contour plots.

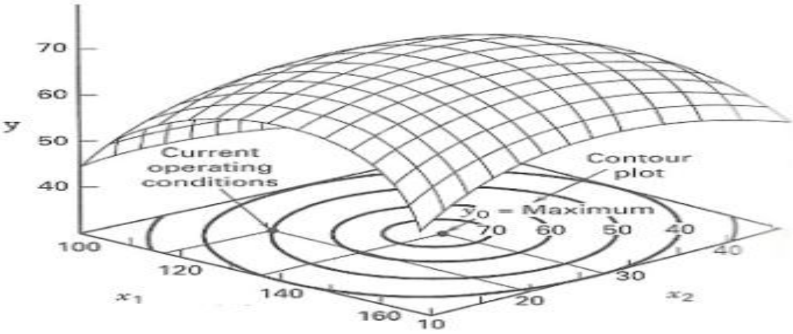


Figure 3.2: Contour Plot

There are three basic concept involved in the design procedure of the response surface methodology:

- Designing experiments in series for a more reliable and adequate measurement of response interests.

- Mathematical model design of the second order response surface coupled with the best fittings.
- Extracting the optimal set of parameters that produces the minimum or maximum response value depending on the experiment desire.

3.1.3 Learning Objectives And Outcomes

- The sequential nature for optimizing a process using RSM
- First and second order response surface models, and finding the direction of steepest descent for minimizing or steepest ascent for maximizing the response
- Dealing with multiple responses simultaneously
- The two major response surface designs (Central composite designs (CCD) and Box-Behnken) designs
- Analyzing design cases where the sum of factor levels equals a constant (100%)
- Introductory understanding of designs for computer models [40]

3.1.4 The Sequential Nature Of The Response Surface Methodology Process

Most applications of RSM are sequential in nature.

Phase 0: Firstly, ideas are generated as to which variables or factors are most likely to be important in the response surface study. This is usually called the screening experiment. The purpose is to reduce the candidate variables to a reasonable amount to increase efficiency of the sequential experiments. This helps identify the important independent variables.

Phase 1: The objective of the experimenter is to investigate if the existing setting of the independent variables produces a response that is close to the optimum. If they are consistent with optimum performance, the experimenter must determine an adjustment for the process variables to move the process towards the optimum. The first-order model and steepest ascent (descent) is applied considerably in this phase of RSM

Phase 2: Phase 2 is initiated when the process is close to the optimum. Here, the experimenter tries to improve the accuracy of the true response function within a relatively close region around the optimum, because the true response surface usually exhibits curvature near the optimum. A second-order model, usually a polynomial is applied. Once an acceptable approximating model is acquired, the model is then analyzed to determine the optimum conditions for the process.

The sequential experimental process is usually performed within some acceptable regions of the independent variable space called region of interest, operability region or experimentation region.

Figure 3.3 shows a description of a response surface method n three dimension, however it is four dimensional spaces that are actually represented. The ideal case will be imagined where there is actually a 'local optimum '. [40]

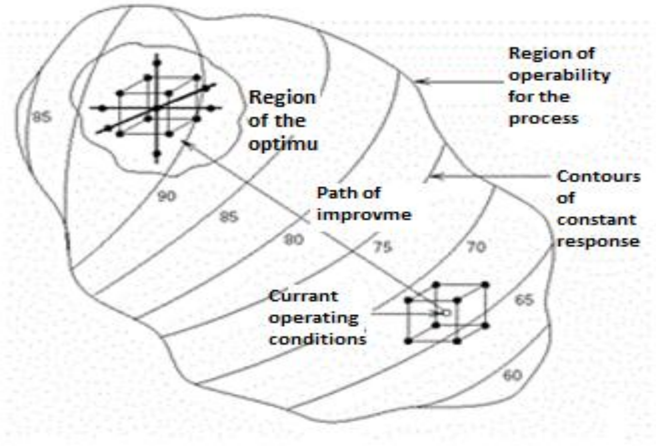


Figure 3.3: The sequential nature of RSM [40]

3.2 NORSOK Standards

The standards of NORSOK are developed by Norwegian petroleum industry to maintain value adding, adequate safety and cost effectiveness for petroleum industry developments and operations. In addition, the NORSOK standards are set to replace oil companies' specifications and serve as references for regulating standards. Currently, there are about 79 national NORSOK standards in use [3]. Fig 3.4 gives a description of NORSOK technical standards

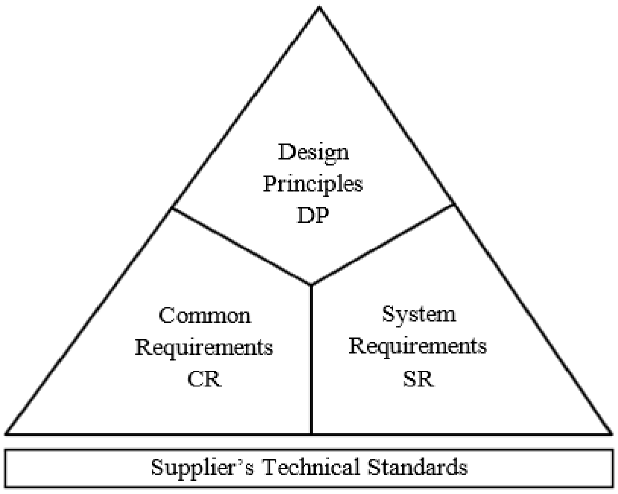


Figure 3.4: Standardization Structure for the NORSOK Standards [3]

There are three different NORSOK standard categories:

- **Design Principles (DP)**

The Design Principles standards are basic criteria for design of plants and systems and selection of main equipment. The required documents are:

- ❖ Operational Requirements
- ❖ Drilling Facilities
- ❖ Technical Safety
- ❖ Working Environment
- ❖ Environmental Care
- ❖ Material Selection
- ❖ Coding System.

The Design Principles clearly explains the operator's basic criteria and is used for the conceptual design throughout engineering aspects of the project development.

- **Common Requirements (CR)**

The Common Requirements standards are regulatory requirements for component variation control. The primary documents are:

- ❖ Technical requirements to design, fabrication, installation, mechanical completion and commissioning.
- ❖ Variation control for the components present in the tables, equipment data sheets and drawings.
- ❖ Variation control by typical drawings.

The application of technical variation control for components permits the use of standards components that have standard interfaces.

- **System Requirements (SR)**

The System Requirements are requirements for a complete functioning system. The standards are set within strict predefined clauses. The system requirements are applied to supplier selection during purchase of systems.

As defined in ISO, the suppliers must clearly state their standards for purchaser’s functional standards.

For selection, the suppliers must adhere to the components standards with standard interfaces as clearly stated by NORSOK's Common Requirements. The competence and competitiveness of the supplier’s shall be applied in optimizing their system based on standard components. This step shall ensure repeated deliveries of standard systems for suppliers.

The suppliers of the components must adhere to the standardized, repeatable technical requirements and must be able to standardize their deliveries. And all the documents of the suppliers must be standardized. Technical standards must also be set by the supplier’s based on the NORSOK standards [3].

The combination of both ISO and NORSOK are the recognized basis for the regulations enforced on the Norwegian continental shelf, and Norway has the so-called function-based regulations, where standards play an important role in the interpretation of various regulatory requirements [4].

The standards are used as reference to provide guidance on how things should be done. The Petroleum Safety Authority uses about half of the standards as part of their regulatory management guide.

3.3 Mean Absolute Error (MAE)

The predicted values of CPR using RSM applied in this thesis are actual values calculated by NORSOK and will be compared based on mean absolute error. The following formula will be used to calculate the error:

$$\mathrm{MAE} = \frac{1}{n}\sum_{j=1}^{n} |y_j - \hat{y}_j|$$

Eq (3.1)

Where:

n = is number of observations.

yj = actual value of CPR.

$\hat{y}j$ =predicted value of CPR.

CHAPTER 4

METHODOLOGY

This chapters explains the response surface method modelling and optimization method that implemented in this thesis, it discuss Central Composite design, the first and second order model and finally Determination of the optimal conditions**.**

4.1 Central Composite Design (CCD):

The CCD is developed through sequential experimentation. It consists of factorial point (from a 2^k design) k represents the number of the factors, central point, and axial points. During the experimentation, if the first-order model a lack of fit evidence, subsequently axial points are added to quadratic terms therefore producing more center points to develop CCD. Two parameters from the CCD design running from the design center are number of center point's **m** at the origin and the distance $\boldsymbol{\alpha}$ of the axial runs.

There are several ways of selecting $\boldsymbol{\alpha}$ and **m**. First, CCD could run in incomplete block. A block is defined as a set of relatively homogeneous experimental conditions giving the experimenter an option of dividing the experiments into groups that are run in each block.

An incomplete block design is applied when all treat treatment combinations cannot be run in each block. To protect the shape of the response surface, the block treatment effect must be orthogonal to the treatment effects. Choosing the correct $\boldsymbol{\alpha}$

and **m** in factorial and axial block make this possible. In addition, **α**and **m** can be chosen in a manner that the CCD is not blocked. At some point, if the precision of the estimated response surface is **x** is only dependent on the distance x and not the direction, then the resulting design is said to be rotatable. The rotatable design allows equal precision of estimation of the surface in all directions. APPENDIX A shows an example of three factors of CCD.

To make the CCD design rotatable, using either α =$2^{k/4}$ for the full factorial.

For this study:

m: the number of center points =6

Star points =6

Factorial points = 8

α = 1

4.2 First Order Model

In practical applications of RSM, it is necessary to develop a fitting model for the response surface, and it is typically driven by some unknown physical mechanism. RSM consists of the experimental strategy for exploring the space of the process independent variables, empirical statistical modeling to develop an appropriate relationship between the yield and the process variables, and optimization methods for finding the levels or values of the process variables that produce desirable values of the responses. In general, the experimenter is concerned with a product, process/system involving a response variable Y that depends on the k process independent variablesx_1,x_2,…., x_k (i.e., the process parameters). To optimize Y, a suitable mathematical approximation for the function / must be developed. That can be expressed as:

$$y = \eta + \varepsilon_{exp} \qquad \text{Eq (4.1)}$$

Where ε_{exp} represents the noise or experimental error observed in the response, usually representing a random variable with zero mean and variance σ^2 . Assuming that there is a deterministic relationship f between η and (x_1,x_2,…., x_k) we can write:

$$y = f\,(x_1, x_2, \ldots, x_k) + \varepsilon_{exp} \qquad \text{Eq (4.2)}$$

$$\text{With } E(y) = \eta \text{ and Variance}(y) = \sigma^2$$

The surface represented by f (x_1,x_2,…., x_k) is called a response surface.

K: represents the number of variables which are three parameters in this study.

4.3 Second Order Model

RSM was used to optimize the CPR in crude oil transportation pipeline. A Central Composite Design (CCD) was used in the optimization of process variables with three factors at three levels with 20 runs, including 6 central points; APPENDIX A shows the factors and there levels. The responses function Y was partitioned into linear, quadratic, and interactive components. Experimental data were fitted to the second-order regression equation.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum \sum_{i \le j} \beta_{ij} x_i x_j + \varepsilon$$

Eq(4.3)

Where: i= 1, 2, 3

j= 1, 2, 3

β_0, b and B contain estimates of the intercept, linear and second-order coefficients, respectively.

Y: is the yield (output variable) which is corrosion penetration rate

x_i, x_j: denote the independent variables

β_0: is the constant term

β_i: represents the coefficients of the linear parameters

β_{ii}: represents the coefficients of the quadratic parameter

β_{ij}: represents the coefficients of the interaction parameters

ε: is the random error

4.4 Determination Of The Optimal Conditions

The surfaces generated by linear models can be used to indicate the direction in which the original design must be displaced in order to attain the optimal conditions. However, if the experimental region cannot be displaced due to physical or instrumental reasons, the research must find the best operational condition inside the studied experimental condition by visual inspection. For quadratic models, the critical point can be characterized as maximum, minimum, or saddle. It is possible to calculate the coordinates of the critical point through the first derivate of the mathematical function, which describes the response surface and equates it to zero. The quadratic function obtained for three variables as described below is used to illustrate the minimization method that used in this thesis:

Min y = b_0 + b_1x_1+ b_2x_2 +b_3x_3+ $b_{11}x_1^2$+ $b_{22}x_2^2$+ $b_{33}x_3^2$+$b_{12}x_1x_2$+$b_{13}x_1x_3$+ $b_{23}x_2x_3$ Eq (4.4)

$$65.4<=x_1<=91.7$$

$$54<=x_2<=823$$

$$3.57<=x_3<=3.66$$

$$\frac{\partial y}{\partial x_1}= b_1+2b_1x_1+b_{12}x_2+b_{13}x_3=0 \qquad \text{Eq (4.5)}$$

$$\frac{\partial y}{\partial x_2}= b_2 +2b_2x_2+b_{12}x_1+b_{23}x_3=0 \qquad \text{Eq (4.6)}$$

$$\frac{\partial y}{\partial x_2}= b_3+2b_3x_3+b_{13}x_1+b_{23}x_2=0 \qquad \text{Eq (4.7)}$$

(x_1 , x_2 and x_3): stand for temperature, pressure and PH, respectively.

Thus, to calculate the coordinate of the critical point, it is necessary to solve the first grade system formed by Equations. (4.5), (4.6) and (4.7) and to find the (x_1 , $x_2$and x_3) values.

The visualization of the predicted model equation can be obtained by the surface response plot. This graphical representation is an n-dimensional surface in the (n +1) -dimensional space. Usually, a two-dimensional representation of a three-dimensional plot can be drawn. Surface plot at the next chapter shows the minimum value of the CPR clearly in the next chapter by holding one of the three factors at the middle of the range as shown at table 4.1 at the APPENDIX B.

Chapter 5

IMPLEMINTATION OF RESPONSE SURFSCE METHODOLOGY

5.1 Introduction

For this thesis, response surface method (RSM) will be used to develop the mathematical model by study the effect of the three parameters selected on the response (CPR).

Central composite design (CCD) is a primary design technique in response surface methodology. This technique is usually used for optimization process.

There are many parameters affect corrosion penetration rate of (Sharara field – Zawia terminal) pipeline in this study. Akakus Oil Operation export pipeline has two parts, the South section running 340 km from NC-115 to Hamada Booster Pump Station (NC-8) and the North section running 383 km from Hamada to Zawia Terminal.

The south section line NC-115 to Hamada booster pump station NC-8 was chosen to apply study on it.

The operating parameters were recorded daily for 12 months, they are pressure, temperature and PH and there corresponding range are showing in TABLE 5.1 in Appendix C.

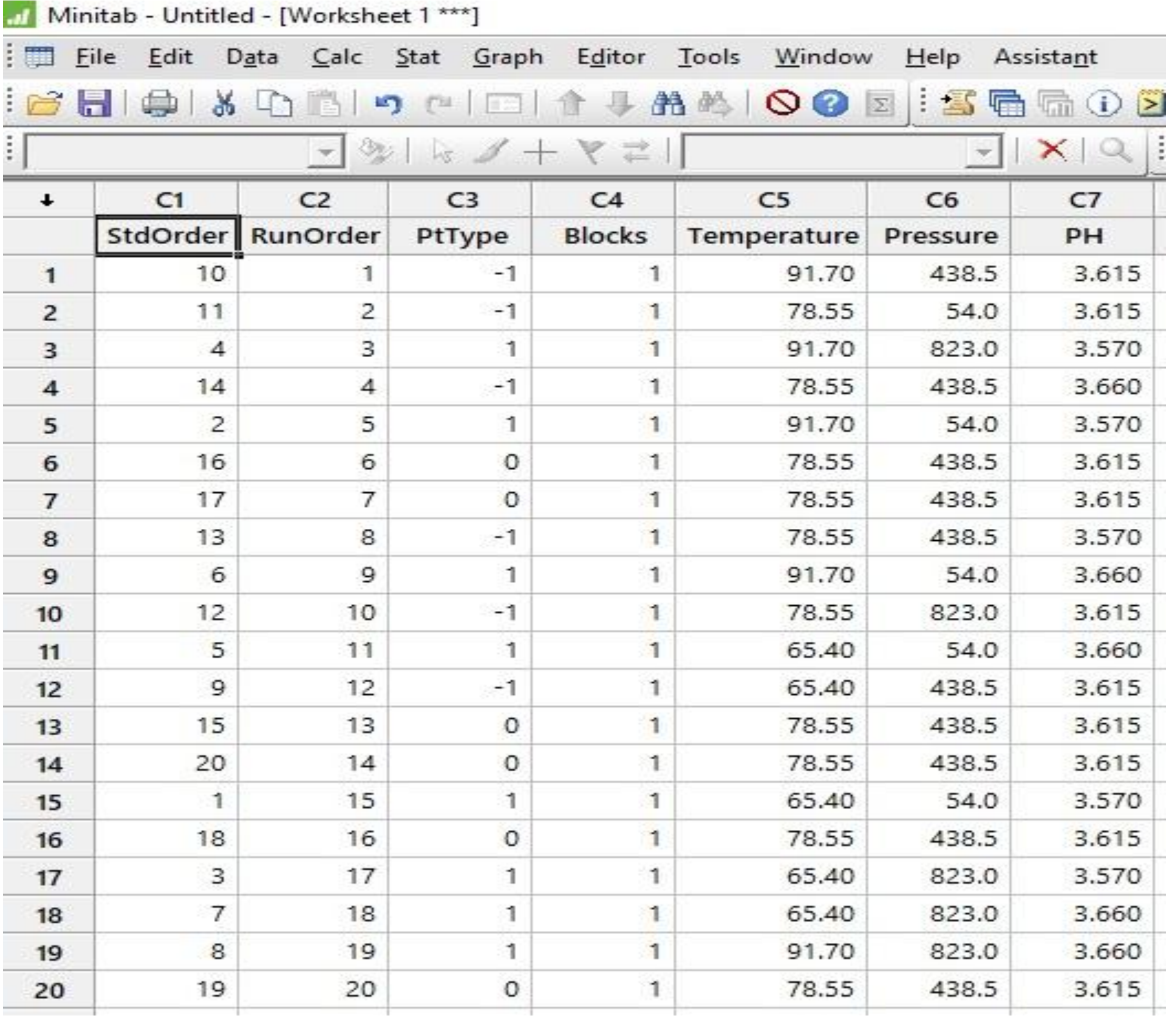
5.2 Response Surface Modeling

Once the parameters levels were selected, then next procedure is designing the experiments.

5.2.1 Central Composite Design

The parameters selected and their values are the input to the software (MINITAP17), a DOE model will generated automatically randomly twenty run coupled with specific parametric settings. As shown in Table 5.2:

Table 5.2: Design of RSM



↓	C1	C2	C3	C4	C5	C6	C7
	StdOrder	RunOrder	PtType	Blocks	Temperature	Pressure	PH
1	10	1	-1	1	91.70	438.5	3.615
2	11	2	-1	1	78.55	54.0	3.615
3	4	3	1	1	91.70	823.0	3.570
4	14	4	-1	1	78.55	438.5	3.660
5	2	5	1	1	91.70	54.0	3.570
6	16	6	0	1	78.55	438.5	3.615
7	17	7	0	1	78.55	438.5	3.615
8	13	8	-1	1	78.55	438.5	3.570
9	6	9	1	1	91.70	54.0	3.660
10	12	10	-1	1	78.55	823.0	3.615
11	5	11	1	1	65.40	54.0	3.660
12	9	12	-1	1	65.40	438.5	3.615
13	15	13	0	1	78.55	438.5	3.615
14	20	14	0	1	78.55	438.5	3.615
15	1	15	1	1	65.40	54.0	3.570
16	18	16	0	1	78.55	438.5	3.615
17	3	17	1	1	65.40	823.0	3.570
18	7	18	1	1	65.40	823.0	3.660
19	8	19	1	1	91.70	823.0	3.660
20	19	20	0	1	78.55	438.5	3.615

Based on the given runs, the generated parameters were reentered into the software (NORSOK M-506) to calculate the response as actual values of (CPR), as shown in table 5.3, in APPENDIX D.

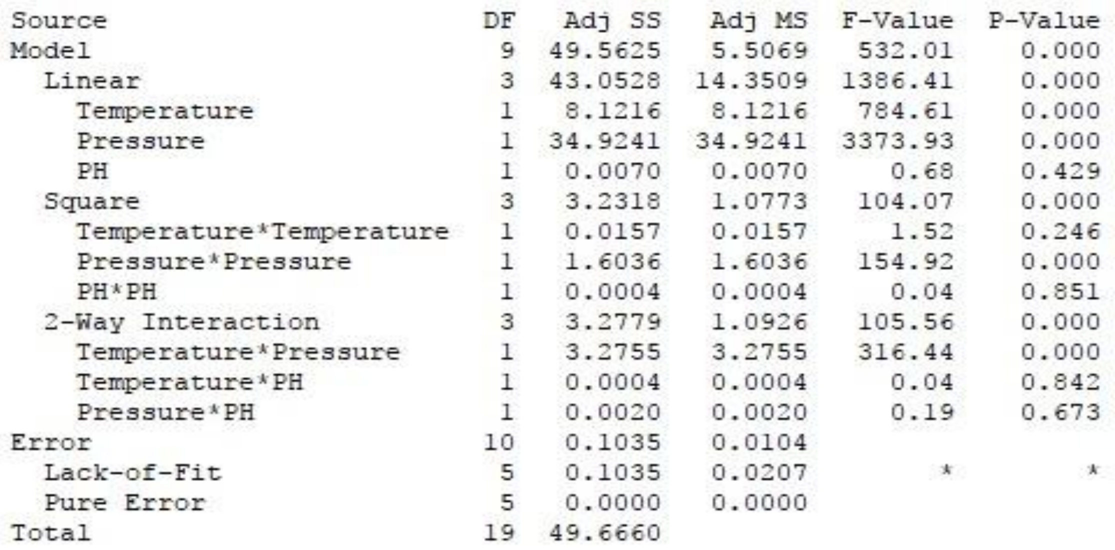
The regression parameters of the developed model of the response with static significance were calculated, the main interactive relationship between the experimental parameters and response were evaluated.

The predicted CPR (RSM) will be the result of predict the 20 runs and using actual CPR as the response in response surface method. Table 5.3 in APPENDIX D shows the actuals CPR, the predicted CPR (RSM), the absolute error MAE.

5.2.2 Response Surface Regression

Analysis of Variance

Table 5.4: ANOVA Table



```
Source                        DF   Adj SS   Adj MS  F-Value  P-Value
Model                          9  49.5625   5.5069   532.01    0.000
  Linear                       3  43.0528  14.3509  1386.41    0.000
    Temperature                1   8.1216   8.1216   784.61    0.000
    Pressure                   1  34.9241  34.9241  3373.93    0.000
    PH                         1   0.0070   0.0070     0.68    0.429
  Square                       3   3.2318   1.0773   104.07    0.000
    Temperature*Temperature    1   0.0157   0.0157     1.52    0.246
    Pressure*Pressure          1   1.6036   1.6036   154.92    0.000
    PH*PH                      1   0.0004   0.0004     0.04    0.851
  2-Way Interaction            3   3.2779   1.0926   105.56    0.000
    Temperature*Pressure       1   3.2755   3.2755   316.44    0.000
    Temperature*PH             1   0.0004   0.0004     0.04    0.842
    Pressure*PH                1   0.0020   0.0020     0.19    0.673
Error                         10   0.1035   0.0104
  Lack-of-Fit                  5   0.1035   0.0207        *        *
  Pure Error                   5   0.0000   0.0000
Total                         19  49.6660
```

Table 5.3 shows that pressure, temperature and the interaction between (pressure*pressure and temperature*pressure) has significant effect on the (CPR), because there p-value is less than 0.05.

The p-value for PH is higher than 0.05 so it doesn’t affect the (CPR), as well as the interaction between (pressure*PH, PH*PH, PH*temperature and temperature*temperature).

5.3 Estimated regression coefficients for CPR

Table 5.5 shows the regression coefficient for corrosion penetration rate, the highlighted rows have significant effects on CPR.

Table 5.5: Estimated regression coefficients for CPR

Term	**Coe.**	**P-value**
Constant	71	0.000
Temp.	0.127	0.000
P.	0.00271	0.000
PH	- 42	0.429
Temp.*Temp.	- 0.000437	0.246
P.*P.	- 0.000005	0.000
pH*PH	5.9	0.851
Temp.*P.	0.000127	0.000
Temp.*pH	- 0.0125	0.842
P.*PH	- 0.00090	0.673

5.3.1 Regression Equation in Uncoded Units

CPR = 71 + 0.127 Temperature + 0.00271 Pressure - 42 PH - 0.000437 Temperature*Temperature - 0.000005 Pressure*Pressure + 5.9 PH*PH + 0.000127 Temperature*Pressure - 0.0125 Temperature*PH - 0.00090 Pressure*PH

5.4 Estimation of the Effect of the Three Parameters

Response surface plot and contour plot were also generated to explain simultaneously the effect of any two parameters and CPR.

Figure 5.1 shows the interaction effect of pressure and pH on CPR and the temperature is constant at (78.55F°) by three dimensional response surfaces.

Decreasing the pressure from (823 psi) to (54 psi), leads to a corresponding decrease in CPR. Therefore, PH value doesn’t affect the CPR.

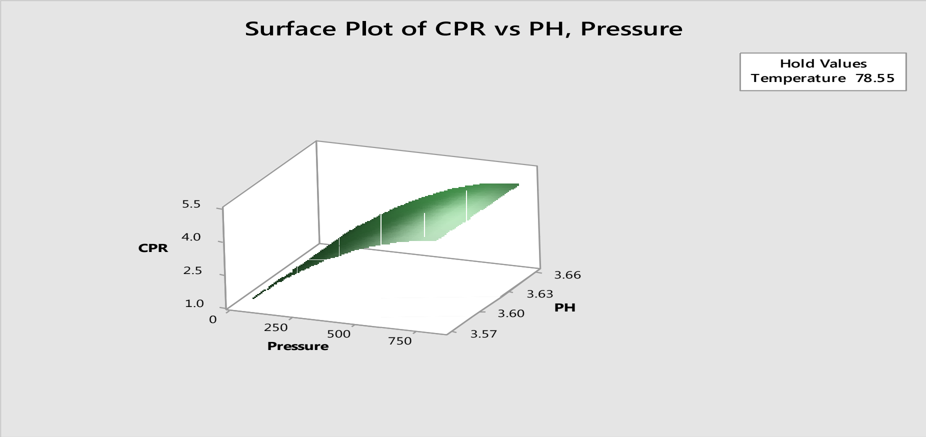


Figure 5.1: between pH and P on CPR Surface plot of interaction

Figure 5.2 shows the interaction effect of temperature and pH on CPR and the pressure is constant at (438.5 psi) by the three- dimensional response surfaces.

Decreasing the temperature from 91.7F° to 65.4F° leads to a corresponding decrease in CPR. Therefore, PH value doesn’t affect the CPR.

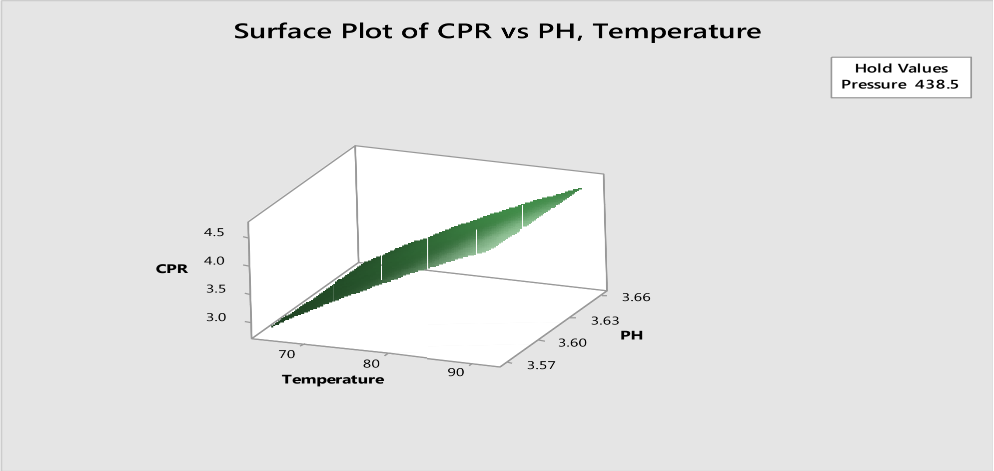


Figure 5.2: Surface plot of interaction between pH and Temp on CPR

Figure 5.3 shows the interaction effect of temperature and pressure on CPR and the PH is constant at (3.615) by the three- dimensional response surfaces.

Decreasing the temperature from 91.7F° to 65.4F° and decreasing pressure from (823 psi) to (54 psi) leads to a corresponding decrease in CPR.

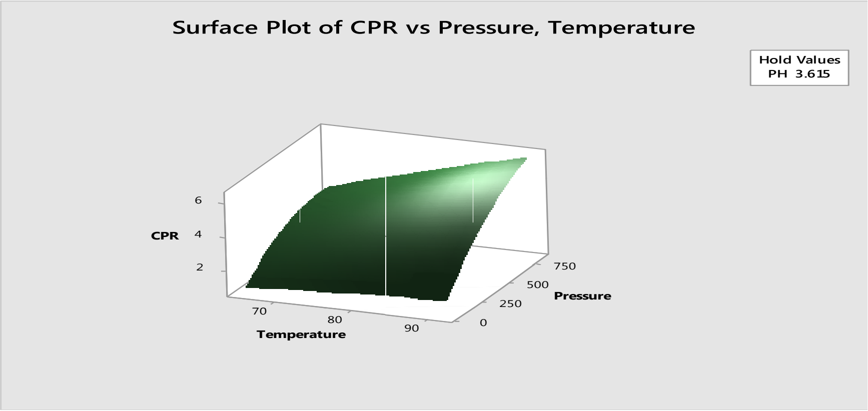


Figure 5.3: Surface plot of interaction between P and Temp on CPR

Figure 5.4 shows the interaction analysis using a contour plot, between pressure and PH. The temperature for this analysis was set constant 78.55F°. From this plot, we can observe that the best value for CPR can be obtained at low pressure value and PH value doesn't affect.

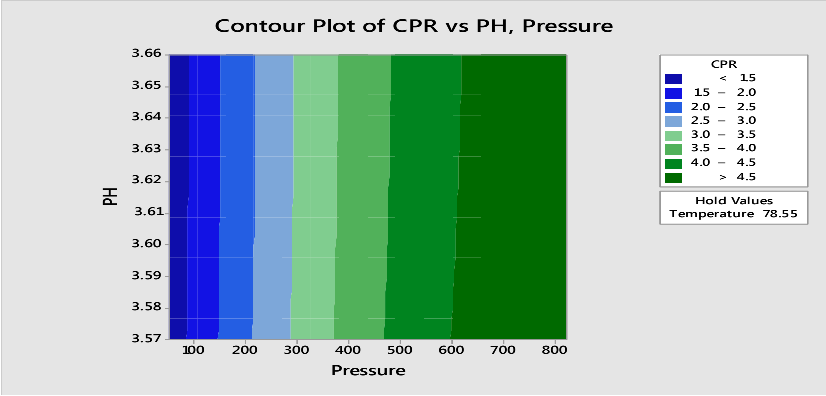


Figure 5.4: contour plot of interaction between P and pH on CPR

Figure 5.5 shows the interaction analysis using a contour plot, between pH and temperature. The pressure for this analysis was set constant (438.5 psi). From this contour plot, we can recognize that the best value for CPR can be obtained at low temperature value and PH value doesn't affect.

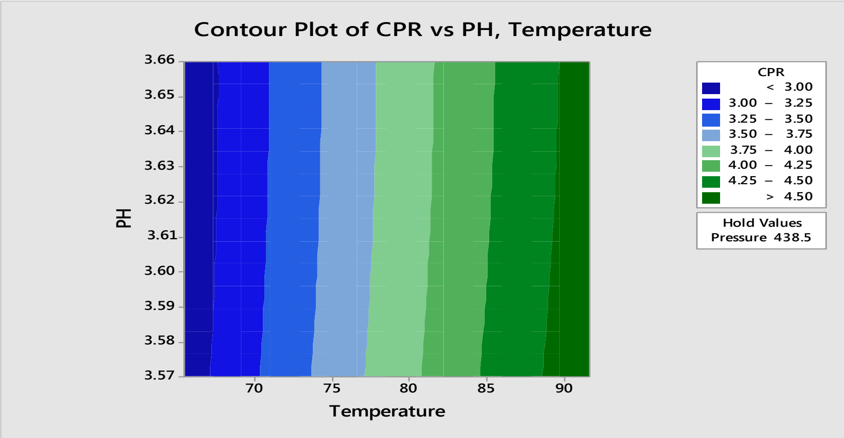


Figure 5.5: Contour plot of interaction between pH and temperature on CPR

Figure **5.6** shows the interaction analysis using a contour plot, between pressure and temperature the pH for this analysis was set constant (3.615). From this plot, we can observe that the best value for CPR can be obtained at low pressure value and low temperature value.

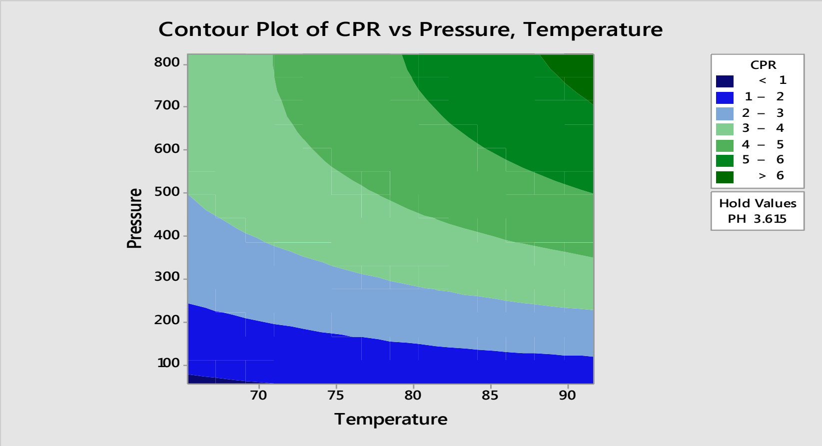


Figure 5.6: Contour plot of interaction between pressure and temperature on CPR

5.5 Response Optimization

To determine the optimal working parameters, Figure 5.7 was generated.

The values in red represent the operating parameters to obtain a minimum CPR are shown in figure 5.7, and it also shows hoe the individual parameter in each column affects the response when the other parameter is held constant. At the upper left corner, D is the composite desirability and d represents is the individual desirability.

The optimization plot as shown in Figure 5.7, It shows that the optimum input values for the all parameters using response optimizer. The optimum values for the parameter are: Optimum temperature is 65.4 F, Optimum pressure is 54 psi, and Optimum pH is 3.6218. As shown an APPENDIX E.

And the optimal CPR with this parameters values is y = 0.8386 mm/yr.

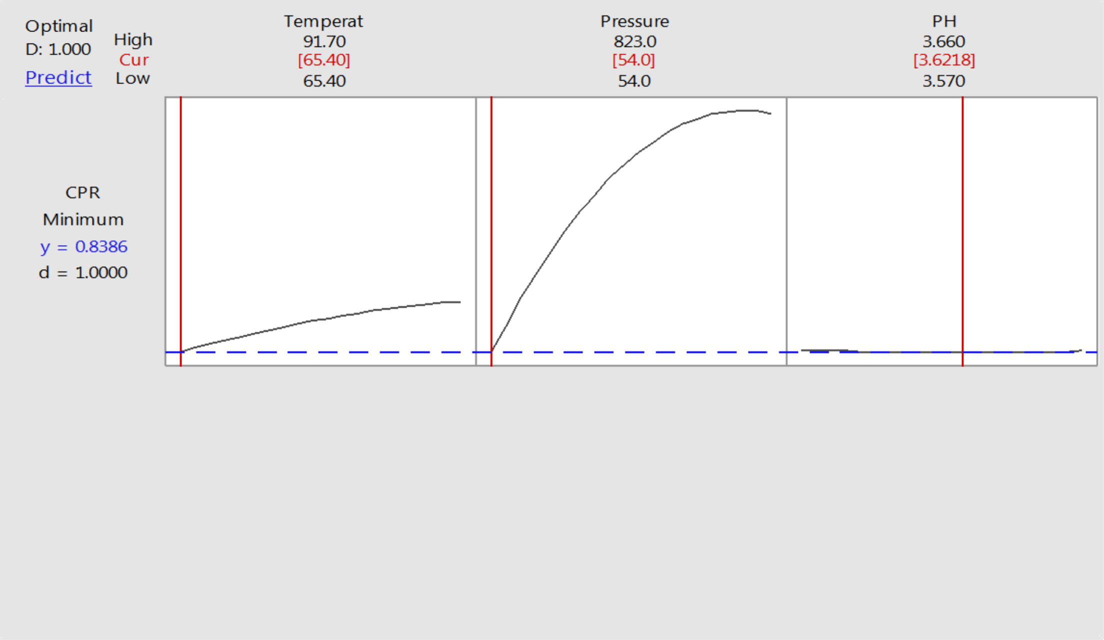


Figure 5.7 optimizing operating parameters for CPR through desirability function approach

Chapter 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

From this study the following points were concluded:

- Out of three parameters, pressure and temperature are the most important and influential parameters that affect the corrosion penetration rate, pH have no effect on it.
- The mathematical model developed clearly shows that the corrosion penetration rate decreasing with decreasing the pressure and temperature.
- The results of ANOVA and the confirmation runs verify that the developed mathematical model for corrosion rate parameters shows excellent fit and provide predicted values of corrosion penetration rate that are close to the experimental values, with a 95 per cent confidence level .
- It can be concluded that interaction between most factors has no significant effect since the p-Value of the interactions are more than 0.05.
- The 3D surface counter plots are useful in determining the optimum condition to obtain particular values of corrosion penetration rate.
- Response surface optimization shows that the optimal combinations of parameters are (65.4 F°, 54 psi, 3.6218) for temperature, pressure, pH respectively.

- This study shows that the empirical models developed using response surface methodology can be used to predict the corrosion penetration rate within 4.7467% MAE.
- The response surface methodology (RSM) combined with the design of the experiments (DoE) is a useful technique for predicting, modeling, optimization of corrosion penetration rate. Relatively, a small number of designed experiments are required to generate information that is useful in developing the predicting equation for corrosion penetration rate.
- This procedure can be used to predict the corrosion penetration rate within the range of parameter of Shararra Zawia pipeline. However, the validity of the procedure is mostly limited to the range of factors considered in the study.

6.2 Recommendations

6.2.1 Recommendations For The Company

- Covering the crude oil transportation pipelines with a heat insulating layers to control the temperature with the optimum value (65.4F°).
- Distribute the pumps by making small station along the transportation pipelines, Instead of a general pump station, to make the pressure constant in the pipe with optimum value (54psi).

By Applying this recommendations CPR at the crude oil transportation pipe will decrease to be (0.8386mm/yr.).

6.2.2 Recommendation For Future Studies:

Future studies may involve the prediction of CPR using the same method with different parameters such as: Viscosity, H2S, Chloride and salinity. Also other techniques such as Artificial Neural network and Surgeon fuzzy might be implemented and their results could be compered.

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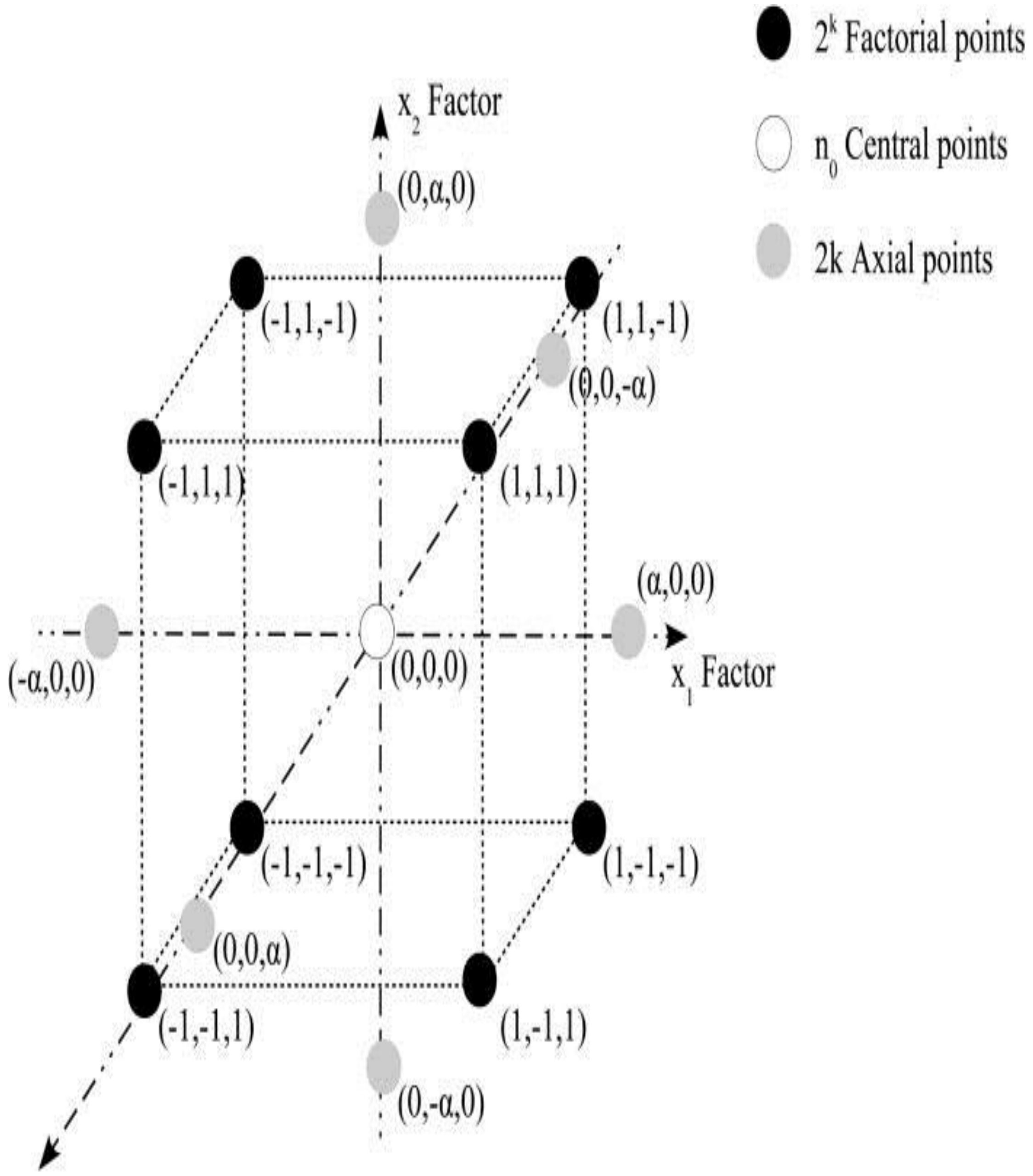
APPENDICES

Appendix A: Three-factor central composite design of experiments



Appendix B: Independent variables and their levels used for CCD:

TABLE 4.1: Independent variables and their levels used for CCD

VARIABLES	FACTORS	LEVELS		
	X	-1	0	1
TEMPRATURE (F°)	X1	65.4	78.55	91.7
PRESSURE (psi)	X2	54	438.5	823
PH	X3	3.57	3.615	3.66

Appendix C: the operating parameters and corresponding ranges

TABLE 5.1: operating parameters and corresponding ranges

Parameters	**Notation**	**Unit**	**Range**	
			Lower value	**Upper value**
Temperature	Temp	F°	65.4	91.7
Pressure	P	psi	54	823
pH	pH	-	3.57	3.66

Appendix D: The actual CPR (CPR), Predicted CPR (RSM) and absolute error AE

Table 5.2: The actual CPR (CPR), Predicted CPR (RSM) and absolute error AE.

CPR (A)	RSM (B)	AE (C)=(A-B)
4.808	4.63382	0.17418
1.078	1.17582	0.09782
6.378	6.44022	0.06222
3.781	3.79362	0.01262
1.364	1.39162	0.02762
3.813	3.80825	0.00475
3.813	3.80825	0.00475
3.845	3.84662	0.00162
1.341	1.35512	0.01412
4.997	4.91342	0.08358
0.913	0.84722	0.06578
2.643	2.83142	0.18842
3.813	3.80825	0.00475
3.813	3.80825	0.00475
0.928	0.85422	0.07378
3.813	3.80825	0.00475
3.361	3.34332	0.01768
3.305	3.27382	0.03118
6.271	6.34122	0.07022
3.813	3.80825	0.00475
4.808	4.63382	0.17418
Total Mean Absolute Error		0.047467

Appendix E: Response Optimization OF CPR

TABLE 5.6: Response Optimization of CPR

Solution	Temperature	Pressure	PH	CPR Fit	Composite Desirability
1	65.4	54	3.6218	0.8389	1