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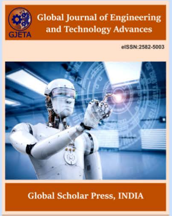

(Research Article)

An experimental design approach for investigating the influence of various factors on wax deposition in production tubing and pipelines

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Abstract

This research work employed the design of experiment approach to investigate the influence of various factors including the inhibition concentration, crude oil temperature and speed of rotation on wax deposition in production tubing and pipelines. A combination of Taguchi orthogonal array of designed experiments with a subsequent application of a standard response surface methodology based central composite design was carried out using the StatEase DesignExpert Software Version 12. The individual effects of variables and its interaction effects towards the dependent variables were studied with the shear rate/degree of viscosity reduction taken as the dependent variable. The results of the study showed that less wax deposition inferred from the degree of viscosity reduction was significantly affected by the crude oil temperature and speed of rotation. The 2FI model was selected based on the significant lack of fit obtained. Model equations were derived based on the results and the predicted values of the response (shear rate/degree of viscosity reduction were obtained at a sufficient degree of correlation. Thus, the Design Expert can be a valuable tool to quantify and detect the special relationships of two of more factors known as interactions regarding how these factors could affect a process, especially for screening purpose.

Keywords: Design of Experiment; Wax Deposition; Model; Optimization

1. Introduction

To meet up with world energy demand, the petroleum industry has explored and produced petroleum from extreme environment like deep offshore. Due to the operating conditions of high pressure and low temperature in this environment, hydrates and wax precipitation and deposition are frequent occurrences in offshore production. Wax are components of crude that exist in liquid form at reservoir condition but precipitate out of solution as the fluid temperature reduces. They can be paraffin (C_{18}-C_{36}) or naphthenic (C_{30}-C_{60}). Waxy crude may also contain low amount of asphaltenes, resins and organometallics [1]. Wax crystallization is a major cause of non-Newtonian behavior in crude oil which affects the flow properties of the crude (viscosity).

Most crude oil in the Niger Delta have an amount of heavy paraffinic molecules dissolved under reservoir conditions. Wax remains in solution until operating conditions are favourable to its precipitation, a condition caused by changes in the temperature–pressure equilibrium of the crude oil. As the oil temperature decreases the paraffin may cause gel formation that consist of wax crystals in a viscous matrix. This circumstance may occur when the pipeline carrying the crude oil is being shut down for operational or emergency reasons in locations with low ambient. Waxy crude oils are non-Newtonian fluids they deviate from Newtonians law of viscosity which states that the shear stress between adjacent fluid layers is proportional to the velocity gradients between the two layers. That is, the relation between the shear stress and the shear rate in waxy crude is nonlinear.

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Wax deposition is known to occur when the ambient temperature decreases below the Wax Appearance Temperature (WAT) or cloud point. The cloud point is the temperature below the point which the crude oil is saturated with wax. It is the temperature at which wax crystals start to form. Cloud point can be affected by the apparent molecular weight of solution, solute, and solute weight fraction [2]. The waxy crude exhibits Newtonian fluid behaviour at temperature above the WAT and Non-Newtonian fluid behaviour at temperature below the WAT [3]. The Wax Appearance Temperature can be measured by using Cross Polar Microscopy (CPM).

Waxy crude oil contains significant amount of paraffin wax in the crude oil which is indicated by pour point of the crude oil. The pour point of crude oil is the temperature at which the crude oil is flowing unsatisfactorily. The crude oil will cease to flow as it is cooled down below the pour point due to gelling from paraffin wax in the crude oil [4]. As the paraffin content in the crude oil is higher, the pour point will be higher. Heavy oil exhibits high pour point and high melting point which results to poor fluid properties of the oil, which affects the mobility of the heavy oil. High pour point also could be exhibited by light crude oil with high amount of paraffin content [5].

As waxy crude oil comes to the surface, it will cool down causing the waxy fraction to gel. When precipitated, wax can be deposited anywhere on the components of the production system, both on the subsurface and surface equipment. It could deposit in the reservoir, wellbore, tubing, flow lines, and surface facilities. The operational problems associated with wax precipitation has resulted in huge losses that amount to billions of dollars annually for the oil industry all over the world. [6]. There are three (3) stages in which the wax crystallization occurs these are the crystal nucleation, growth and agglomeration [7]. Wax deposition takes place in production tubing, pipelines and production facilities until the oil goes into the storage tank [8]. This can cause reduction in the internal diameter of tubing thereby resulting in a reduction of crude oil production rate. The wax is also able to settle down inside the surface facilities such as choke and separator which will cause doubt in the integrity of the equipment. As the wax deposits in the pipeline, it causes pumping problems which eventually reduces the pumping capacity of the pump to effectively transport the crude oil. As a consequence, high pressure will be needed to transport the crude oil through the pipeline. At certain point, the deposition of wax will affect the pump and other facilities. In order to fix this; the production of crude oil will be shut down thereby causing loss of profit. On the whole, the presence of the solid waxes will cause several major problems such as wax accumulation on the pipe walls, reduction of flow line section, blockage of filters, valves and pipelines, and reduction or even stoppage of oil production or transportation [9].

The chemical method of preventing wax precipitation in pipelines has captured the interest of researchers due to its effectiveness, low cost, and ease of application. Some of these include, - The wax crystal modifiers which act at the molecular level to reduce the tendency of wax to network and form lattice structures, hence lowering wax gel strength [10]. Dispersants, which is a type of surfactant that helps disperse the wax crystals into the produced oil or water. This dispersing of the wax crystals into the produce oil or water helps prevents the deposition of the wax and also has a positive effect on the viscosity and gel strength. Nanoparticles (NPs) possess high surface area to volume ratio which enhances interaction, hence making it applicable in tackling flow assurance problems in the petroleum industry [11].

Odutola and Allaputa [12] discussed using Aluminum oxide nanoparticles in combating wax precipitation in Nigerian waxy crude oil while Odutola and Idemili [13] reported the successful application of a blend of Poly (ethylene-butene) and nano-aluminium oxide in reducing the viscosity of Nigerian waxy crude oil.

Selecting the optimum wax inhibitor involves carrying out experiments to test out the effect of the inhibitor on various parameters. This can be time and money consuming. Designing an experiment prior to conducting the experiment can significantly reduce experiment cost and help researcher know the important factors in the experiment to focus on. DesignExpert is a statistical software package that is specifically designed to perform the design of experiment (DoE). This software is able to offer comparative tests, screening, characterization, optimization, robust parameter design, mixture designs and combined designs. It can also suggest the minimum number experiments to avoid time wastage [14]. Several researchers used DesignExpert to design their experiments on petroleum production.

Yonguep and Chowdhury [15] used the central composite design (CCD) and the response surface methodology (RSM) in Design-Expert® (V11.0.3.0) to design, model, and optimize the experimental data in their research on crude oil demulsification. This involved selecting two levels, two numeric and one categorical factor from the CDD to study the demulsification efficiency (which was the response). The factors studied were the demulsifier concentration, settling time coded, and the oil to water ratio. All the factors were examined at a high level, low level, and center points denoted as 1, − 1, and 0 respectively. A total number of 52 experimental runs were generated which consisted of 32 factorial points, and 5 center points with the axial point set at $\alpha=1.414$ and 4 levels. The effect of demulsifier concentration, settling time, and oil to water ratio on the effectiveness of demulsifiers was investigated and the best condition for maximum demulsification efficiency was optimized using response surface methodology (RSM) based on the central composite design (CCD). The main objective of this study was to find the optimum values of concentration, oil to water ratio, and settling time to obtain the maximum demulsification efficiency of considered demulsifiers according to the developed models of RSM. It was found that the interaction of the settling time, the demulsifier concentration and the oil to water ratio had a significant impact on the response for the demulsifiers studied. It was noted base on the analysis of variance (ANOVA) results that the demulsifier concentration had more effect on the response as compared to other factors.

Ugwele et al. [16] conducted study on the optimization of process parameters for the regeneration of used mobil oil by acid/clay method using sulphuric acid as washing agent. The process parameters were optimized using Central Composite Rotatable Design (CCRD) of Response Surface Methodology (RSM), with the aid of DesignExpert. The design, which use purity as the response of the experiment, considered three independent factors of acid concentration, settling time and bleaching temperature. Central Composite Design (CCD) of the Response Surface Methodology (RSM) was used in optimizing the reaction conditions for the regeneration of used Mobil oil using acid/clay method. These reaction conditions are bleaching temperature, acid concentration and settling time. The experimental design done with the aid of DesignExpert version 11, considered three independent factors of bleaching temperature, acid concentration and settling time. RSM was used to model the relationship between the process conditions (acid concentration, settling time and bleaching temperature) and the response (purity). The DesignExpert analysis generated about 100 optimum solutions from which one was selected. The purification was carried out at the optimum conditions to verify the selected solution by determining actual purification. The actual purity obtained agreed excellently with the theoretical percentage purity. This was equally affirmed by the alignment of the data points of the predicted and actual values.

Norida et al. [17] studied the application of response surface method design based on rotatable central composite design (CCD) to optimize wax deposit using DesignExpert 7.1.6 software. A standard RSM design called central composite design (CCD) was applied to study the wax deposit variables. The two independent variables studied were the cold finger temperature (A) and experimental duration (B) that were coded at five levels. The CCD includes eight factorial points and five replications at the center point, in which a total of 13 experimental runs were employed to fit a second-order polynomial model using DesignExpert (State-Ease, USA) version 7.1.6. The inhibitor concentration and speed of rotation were set for 5000ppm and 0 rpm respectively for each run. The influence of operating parameters on the weight of wax deposit was investigated using cold finger apparatus. The experimental result indicated that the amount of wax deposit was significant due to factors of cold finger temperature and experimental duration. There was a good match between the experimental and predicted data from the polynomial relationship for each response.

The most complete DOE is a full factorial method, wherein all possible interactions between factors and their levels are considered. But this is still a relatively expensive and error-prone method. Fractional factorial methods are an alternative for DOE which reduce the number of experiments, time and costs of experimental run [14,15,16]. The Taguchi method is one of the simple and effective fractional factorial methods for DOE. This method is a statistical tool for orthogonal arrays (design) with a minimum number of experimental runs. It also arranges various factors for efficient optimization in the experimental conditions and uses analysis of variance (ANOVA) for statistical analysis [17,18].

The Taguchi design is a statistical experimental design method that was developed by Genichi Taguchi in the mid-20th century. It is a robust design method that is widely used in quality control and engineering optimization. The Taguchi design has several advantages that make it an attractive option for many applications [19, 20]. The Taguchi design is focused on achieving robustness in the design, meaning that it is designed to minimize the effects of noise factors, such as environmental changes, that can affect the performance of a system. Besides, the Taguchi design uses orthogonal arrays, which are special types of experimental designs that allow for the efficient estimation of the main effects and interactions of the factors being studied. This leads to more efficient and effective experimentation. In addition, the Taguchi design uses a loss function approach, in which the objective is to minimize the difference between the desired response and the actual response. This approach provides a clear and direct way of defining and measuring success, which can be useful in many applications. Despite its many advantages, however, the Taguchi design is not appropriate for all applications. The Taguchi design is best suited for problems with a small number of factors. For problems with a large number of factors, other design methods, such as the central composite design or response surface methodology, may be more appropriate. One obvious shortcoming is that the Taguchi design assumes that the relationship between the factors and the response is linear. This can be a limitation for complex systems where nonlinear relationships are present [21, 22, 23].

The Central Composite Design (CCD) is a popular design type used in Design of Experiments (DOE) for analyzing the impact of multiple factors on a response variable [24], [25]. It is particularly useful when you have several factors, each with two or more levels, and you want to determine the relationships between the factors and the response variable. By adding center and star points to a full factorial design, the CCD provides a better understanding of the relationship between the factors and the response variable and can be used to optimize the response. The CCD has several advantages over other design types, including improved precision, efficient estimation of the response surface, and the ability to assess the curvature of the response surface. Additionally, the CCD can be used to optimize the response variable by finding the combination of factor levels that result in the desired response [26].

2. Material and methods

2.1. Materials and Equipment

This study experimentally investigates the effect of a blend of polyethylene butene (PEB) and Al_2O_3 nanoparticle on the shear stress of a Niger Delta crude oil sample at varying temperatures. The materials used in this research include a Niger Delta crude oil sample, polyethylene butene (PEB), Al_2O_3 nanoparticle and Xylene.

The Niger Delta crude oil sample has a wax appearance temperature (WAT) of 29°C, a pour point of 10°C, an API gravity of 43.19 and wax content of about 36.6%. The PEB, xylene and nano Al_2O_3 used in this study were obtained from Sigma Aldrich. The Al_2O_3 nanoparticle has a silt size of 75 nm, density of 3.9 g/cm^3, and molar mass of 101.96 g/mol while the PEB has a molecular weight of 84.16 g/mol and density of 0.865 $g/\ cm^3$.

The PEB was prepared into 500 ppm, 1000 ppm, 2000 ppm and 5000 ppm solution by mixing 0.02 ml, 0.04 ml, 0.08 ml and 0.2 ml of PEB, respectively, in 40 ml of xylene (solvent) at continuous stirring in a mixer at 1500 rpm for 30 min. The nanofluid was prepared by mixing 0.01 g of nano-aluminium oxide (Al_2O_3) in 100 ml of xylene (base fluid) continuously using a Hamilton beach mixer at 1500 rpm for 30mins to achieve a homogenous 100 ppm Al_2O_3 nanofluid. The hybrid of polymer/nanofluid inhibitor was obtained by mixing, 1wt% (3 ml) of the nanofluid to 3wt% (9 ml) of each concentration of polymer solution prepared and stirred at 28 °C for 30mins.

An electrical water bath and a chiller were used to condition the crude temperature to the required prior to viscosity readings from the Znn-d12 12—speed rotary viscometer. The dynamic viscosity of the crude sample without inhibitor and the viscosity of the crude oil blended with the polymer and nanoparticle at different temperatures temperature (10ºC, 15ºC, 20ºC, 25ºC and 30ºC) and viscometer speed (1, 2, 3, 6, 30, 60, 90, 100, 180, 200, 300 and 600 rpm) were obtained using the viscometer.

2.2. Experimental Design Concept

DesignExpert is a software tool used in Design of Experiments (DOE) to analyze the impact of multiple factors on a response variable. DesignExpert was employed for studying the various factors affecting wax formation: speed of rotation, temperature, nature/concentration/level of inhibitors. The response variable was defined to be the shear stress or the degree of viscosity reduction (DVR), which is a function of the fluid viscosity. Each factor was tested at two or more levels, depending on the applied designed case, thus the experiments were conducted by varying the levels at two or more ranges of conditions upon testing.

Based on the number of factors, levels, and the number of experimental runs conducted, the design type that best fits the experiment was selected including Taguchi orthogonal array design (Table 1), and response surface methodology central composite design (Table 2). Using the selected design type, the design matrix was set up. This matrix defines the specific conditions under which each experimental run will be conducted. The experiments were then conducted the under the conditions defined in the design matrix.

Upon completion of the experiments, the results (appropriate responses to the designed matrix experimental runs) were entered into the DesignExpert software and the analysis was performed with a bid to understand the impact of each factor on the response variable and identify the most significant factors. Based on the results of the analysis, conclusions have been drawn about the factors affecting hydrate formation and recommendations made for future experiments draw.

Table 1 Design Matrix employed for Taguchi OA with Three Factors at Two Levels

Std	**Run**	**Factor 1**	**Factor 2**	**Factor 3**	**Response 1**
		A:Temperature	**B:Speed of Rotation**	**C:Concentration**	**Shear rate**
		***C**	**Rpm**	**Ppm**	
4	1	Level 2 of A	Level 2 of B	Level 1 of C	27
1	2	Level 1 of A	Level 1 of B	Level 1 of C	16.5
2	3	Level 1 of A	Level 2 of B	Level 2 of C	79.5
3	4	Level 2 of A	Level 1 of B	Level 2 of C	1.5

Response	Name	Units	Observations	Analysis	Minimum	Maximum	Mean	Std. Dev.	Ratio	Transform	Model
R1	Shear rate		4.00	Factorial	1.5	79.5	31.13	33.91	53.00	None	Mean

Table 2 Design Matrix for Response Surface Methodology Centre Composite Design

Std	**Run**	**Factor 1**	**Factor 2**	**Factor 3**	**Response 1**
		A:temperature	**B:speed of rotation**	**C:inhib. levels**	**R1**
		***C**	**Rpm**	**wt%**	
2	1	1	-1	-1	1.5
12	2	0	1.68179	0	2
19	3	0	0	0	1
14	4	0	0	1.68179	2
16	5	0	0	0	1.8
4	6	1	1	-1	9
20	7	0	0	0	1
1	8	-1	-1	-1	2
6	9	1	-1	1	0.5
17	10	0	0	0	1
18	11	0	0	0	1
13	12	0	0	-1.68179	1.5
3	13	-1	1	-1	30
10	14	1.68179	0	0	1
5	15	-1	-1	1	1.5
9	16	-1.68179	0	0	1
11	17	0	-1.68179	0	1
8	18	1	1	1	7.5
15	19	0	0	0	1
7	20	-1	1	1	1.5

3. Results and discussion

Taguchi orthogonal array design has been employed alongside in the work, followed by a Center Composite Design. The CCD has been applied as a full factorial design with additional runs at the center and at the edges of the design space. These extra runs help to assess the curvature of the response surface and provide a better understanding of the relationship between the factors and the response variable. The number of runs in a CCD is dependent on the number of factors and their levels. In this work a 3-factor design with 2 levels for each factor, yielded 3^2 = 9 full factorial runs, plus 3 center points and 2^(3/2) star points for each factor. The center points were run at the average levels of the factors. These runs have been used to determine the average response for the design and to check for any curvature in the response surface while the star points were run at a combination of high and low levels of the factors. These runs help to assess the curvature of the response surface and the effects of the factors on the response variable. The results of the CCD have been used to fit a response surface equation to the data. This equation can be used to predict the response variable for any combination of factor levels.

Half-Normal Plot and Normal Plot of Residues for the Standardized Effects of Factors as Obtained from Taguchi Orthogonal Array Design Evaluation is presented below (Fig. 1) followed by the summary of the standardized effects of the factors under investigation on the degree of viscosity reduction (Table 3). The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. Fig. 3 depicts the Pareto Chart of the Singular Effects of Crude Temperature, speed of Rotation and Inhibitor Concentration on shear rate.

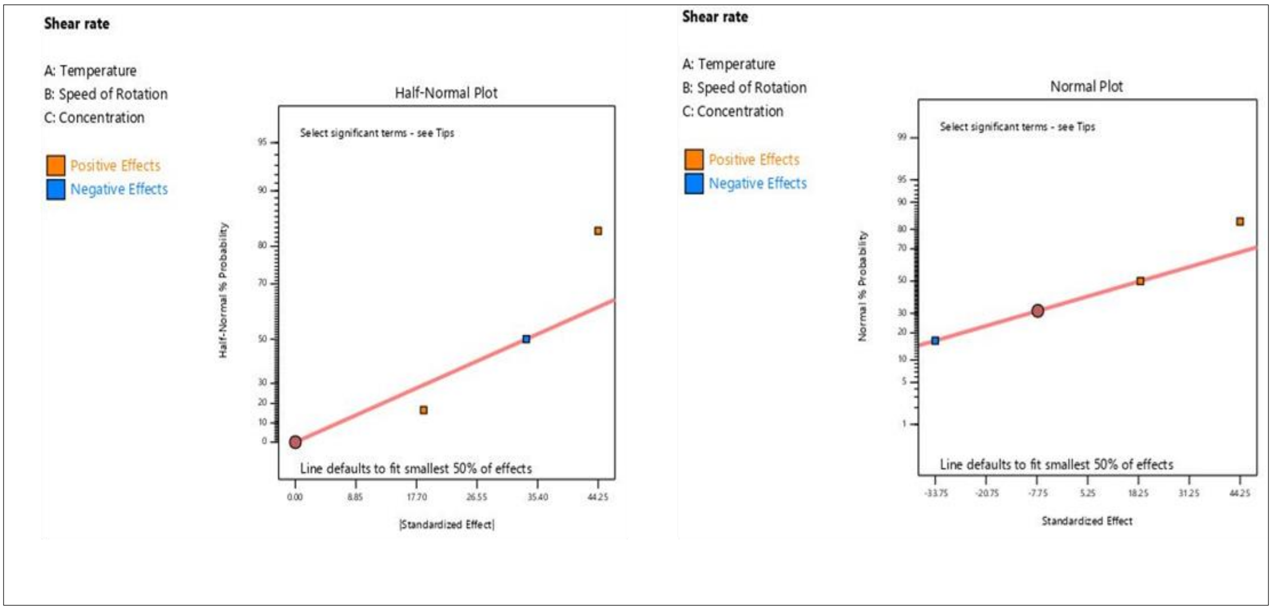

Figure 1 Half-Normal Plot and Normal Plot of Residues for the Standardized Effects of Factors as Obtained fron TaguchiOA Design Evaluation

The most significant factor influencing the response variable at the interval of the factors considered in this particular case (crude temperatures from 100 to 200 below the WAT, speed of rotation from 30 to 600 rpm and inhibitor concentration from 1 to 4%) has been found to be the speed of rotation with nearly 57% contribution. This is attributable to the fact that an increase in the rotation speed will lead to enhanced bulk crude flow and a corresponding increase in the degree of viscosity reduction which ultimately results in lower wax deposition along the pipeline. The second most significant effect is shown by the crude temperature (33% contribution), but in a negative manner. This is obvious from the fact that low temperature (the farther from the WAT the better) would favour wax deposition prevention.

Fig. 4 is a typical response surface diagram, also known as three-dimensional (3-D) diagram. Interaction effects of two independent variables (in this case, the speed of rotation and crude temperature) have been shown with the plot by maintaining one variable at its null point, while carefully varying the other two variables within experimental range.

Table 3 Summary of Effects of the Factors Analysed with TaguchiOA Design

	Term	Aliases	Stdized Effect	Sum of Squares	% Contribution
Require	Intercept	ABC			
Error	A-Temperature	BC	-33.75	1139.06	33.03
Error	B-Speed of Rotation	AC	44.25	1958.06	56.78
Error	C-Concentration	AB	18.75	351.56	10.19
Aliased	AB			Aliased	
Aliased	AC			Aliased	
Aliased	BC			Aliased	
Aliased	ABC			Aliased	
	Lenth's ME		643.25		0
	Lenth's SME		1900.69		0

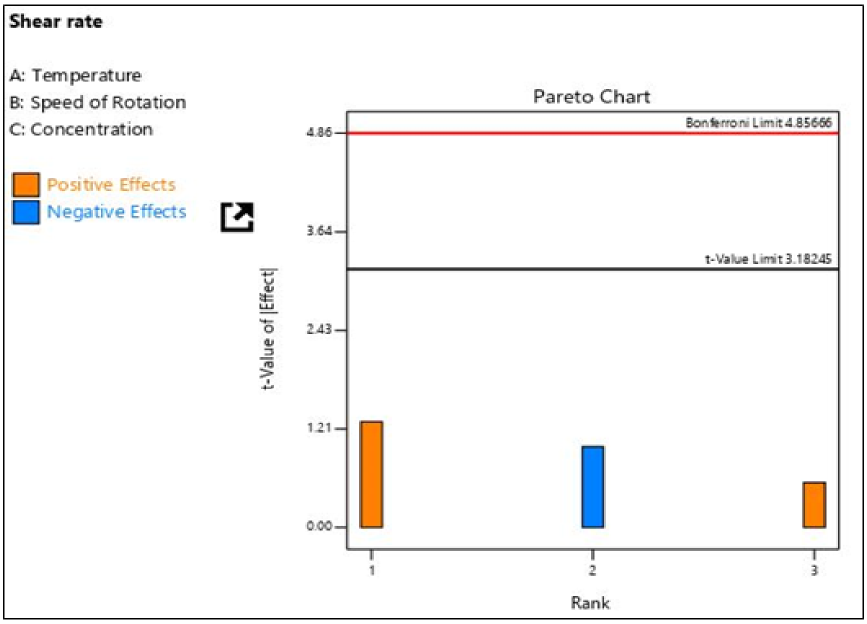

Figure 3 Pareto Chart of the Singular Effects of Crude Temperature, Speed of Rotation and Inhibitor Concentration on Shear Rate

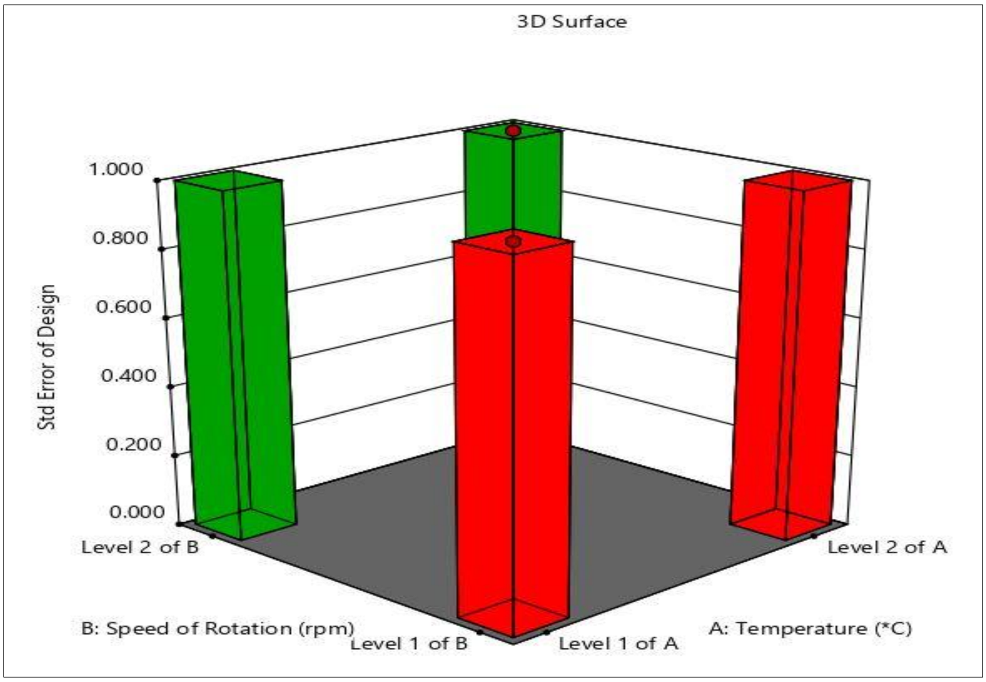

Figure 4 3D Surface Representation of TaguchiOA Design Evaluation

Fig. 4 depicts how the crude oil temperature and speed of rotation (AB interaction), affects the shear rate. It is evident from the Figure that a significantly high level of interactions exists between temperature and speed of rotation, which is also inferable from the AB interaction effect aliased with the effect of concentration (C-AB = 18, 75, equivalent to 10% contribution) (Table 3).

Upon the evaluation of the Response Surface Methodology Centre Composite Design (Figs. 5,6 and Table 5), several models were considered and the summary of model comparisons has been presented in Table 4.

Table 4 Model Comparison for the RSM Centre Component Design

Source	**Sequential p-value**	**Lack of Fit p-value**	**Adjusted R^2**	**Predicted R^2**	
Linear	0.1467	< 0.0001	0.1428	-0.3149	
2FI	0.1188	< 0.0001	0.3171	-1.5950	Suggested
Quadratic	0.6726	< 0.0001	0.2337	-2.2331	
Cubic	0.0590	< 0.0001	0.6629	-22.3258	Aliased

Judging by the lowest sequential p-value the 2FI model was selected and employed for further statistical analysis and the ANOVA table for the 2FI model is presented in Table 5.

Table 5 ANOVA for 2FI model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	443.79	6	73.97	2.47	0.0810	not significant
A-temperature	19.94	1	19.94	0.6657	0.4292	
B-speed of rotation	142.93	1	142.93	4.77	0.0478	
C-inhib. Levels	68.83	1	68.83	2.30	0.1534	
AB	22.78	1	22.78	0.7608	0.3989	
AC	87.78	1	87.78	2.93	0.1106	
BC	101.53	1	101.53	3.39	0.0885	
Residual	389.28	13	29.94			
Lack of Fit	388.74	8	48.59	455.56	< 0.0001	significant
Pure Error	0.5333	5	0.1067			
Cor Total	833.07	19				

The effect of the parameters can be evaluated by F-values or the p-values. A parameter is significant if the F-value is higher than the F-critical or if the p-value is less than the significance level of 0.05. In other words, the p-value is the probability of the F-critical being greater than the F-values of the parameters. If the probability is more than the significance level, it means the parameter is not significant else the parameter is significant. Here once again in Table 5 the significance of the speed of rotation under the conditions studied has been established, the p-value of 0.0478 is less than 0.05. In other words, the speed of rotation significantly and positively affects the degree of viscosity reduction and shear rate. The Model F-value of 2.47 implies there is a 8.10% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case B is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The Lack of Fit F-value of 455.56 implies the Lack of Fit is significant. There is only a 0.01% chance that a Lack of Fit F-value this large could occur due to noise.

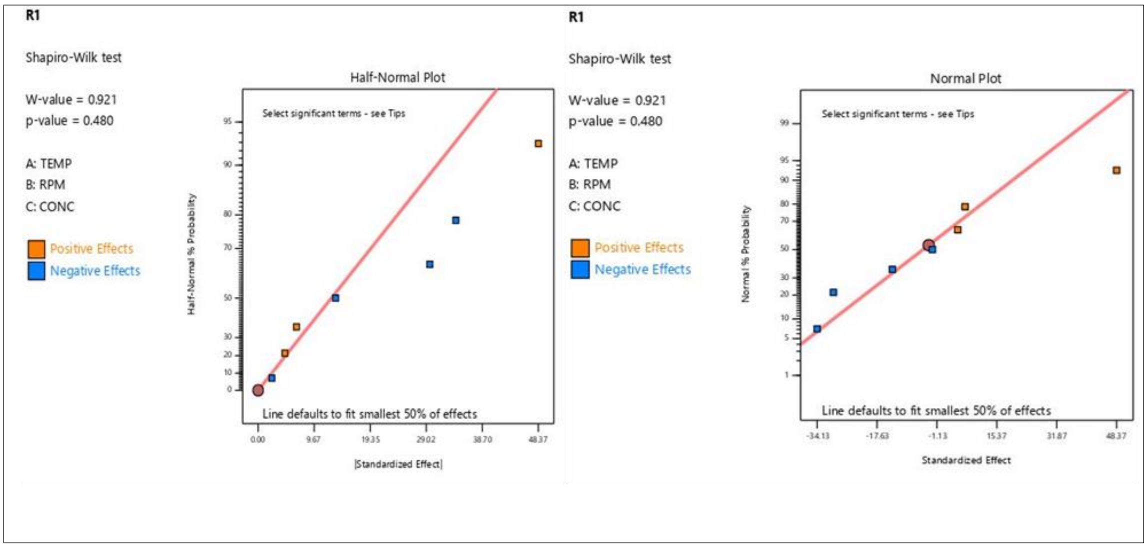

Figure 5 Half-Normal Plot and Normal Plot of Residues for the Standardized Effects of Factors as Obtained from RSM Centre Component Design Evaluation

The coefficient estimate (Table 7) represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings. When the factors are orthogonal the

VIFs are 1; VIFs greater than 1 indicate multi-collinearity, the higher the VIF the more severe the correlation of factors. As a rough rule, VIFs less than 10 are tolerable.

Table 6 Summary of Effects of the Factors Analysed with RSM CCD

Term	Stdized Effect	Sum of Squares	% Contribution
Intercept			
A-TEMP	-34.13	2329.03	25.14
B-RPM	48.37	4680.28	50.52
C-CONC	-13.38	357.78	3.86
AB	-29.63	1755.28	18.95
AC	4.63	42.78	0.4618
BC	-2.37	11.28	0.1218
ABC	6.63	87.78	0.9475
Lenth's ME	75.52		
Lenth's SME	180.73		

Table 7 Estimation of the Factors Coefficients

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	3.44	1	1.22	0.7966	6.08	
A-temperature	-1.21	1	1.48	-4.41	1.99	1.0000
B-speed of rotation	3.24	1	1.48	0.0362	6.43	1.0000
C-inhib. levels	-2.24	1	1.48	-5.44	0.9540	1.0000
AB	-1.69	1	1.93	-5.87	2.49	1.0000
AC	3.31	1	1.93	-0.8672	7.49	1.0000
BC	-3.56	1	1.93	-7.74	0.6172	1.0000

The final model equation has been derived in terms of both the coded factors (equation 1) and the actual factors (equation 2); this can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

$$R1 = 3.44 - 1.21A + 3.24B - 2.24C - 1.69AB + 3.31AC - 3.56BC \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

R1 = 3.44000 -1.20818Temperature +3.23514speed of rotation -2.24496inhib. Levels -1.68750 temperature * speed of rotation +3.31250temperature * inhib. Levels -3.56250speed of rotation * inhib. Levels ……………(2)

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space.

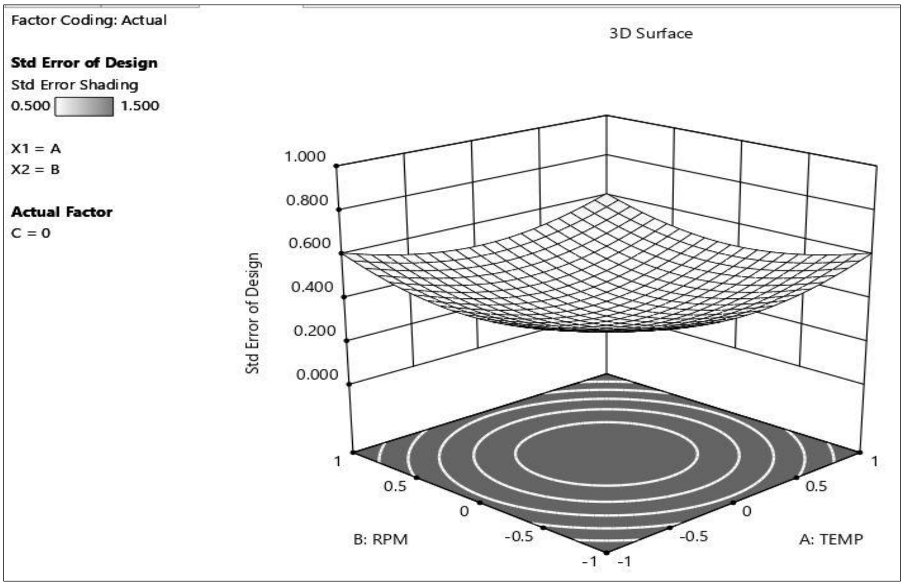

Figure 6 3D Surface Representation of RSM CCD Evaluation

4. Conclusion

It can be deduced from this experimental design study that the speed of rotation and crude temperature have a significant effect on the degree of viscosity reduction/shear rate which is a measure of wax decomposition in production tubing and pipelines. Also significant is the interaction effect caused by aliasing these two important parameters. A 2FI model has been selected and evaluated to yield a model equation useful for predicting the response for given levels of each factor.

Compliance with ethical standards

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Disclosure of conflict of interest

There are no conflicts of interest.

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