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Application of Response Surface Methodology (RSM) for the Modelling and Optimization of Sand Minimum Transport Condition (MTC) in Pipeline Multiphase Flow

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Abstract

This study investigated the influence of three operational parameters (liquid viscosity, pipe diameter and sand concentration) and their interactions on sand minimum transport condition (MTC) in multiphase pipelines using response surface methodology (RSM). Historical data: liquid viscosity (A) at 1, 7, 20, 105, 200, 340 cP; pipe diameter (B) at 0.0776 and 0.10 m; sand concentration (C) at 50 and 200 lb of sand per 1000 bbl of fluid, were correlated with the response (MTC). A two-factor interaction (2FI) regression model was developed and validated prior to optimization studies. The effects of the combination of these factors were also ascertained with 3D plots. The result showed that the predicted data had a reasonable agreement with the experimental data with the values of R^2 (0.9941) and Adj-R^2 (0.9869). The predicted optimum conditions of the operating parameters were observed at liquid viscosity (335.63 cP), pipe diameter (0.08 m) and sand concentration (115.61 lb/bbl) to achieve minimum sand MTC of 0.130242 m/s which were coherent with the experimental optimum conditions 340 cP liquid viscosity, 0.08 m pipe diameter, 125 lb/1000bbl sand concentrations and 0.130242 m/s MTC. Liquid viscosity and pipe diameter were the most significant operating parameters from the 3D plots. The study revealed that the response surface methodology (RSM) is an efficient statistical technique for providing appropriate empirical model for relating the operational parameters, and predicting the optimum operating conditions affecting sand MTC, a veritable parameter in evaluating sand transport in pipeline multiphase flow.

Keywords: *Minimum Transport Condition (MTC); Multiphase Flow; Response Surface Methodology (RSM); Historical Data; Empirical Model, Optimization.*

1. Introduction

In the petroleum industry, one of the main problems encountered during production is sand transport through pipelines [1-2]. Sand production occurs usually in oil and gas reservoirs since majority of the reservoirs are unconsolidated. Massive reductions in oil and gas production rates have been experienced over time due to wormholes [3] and sand deposition on surface and downhole equipment [4]. The risks of frictional pressure loss, microbiologically-influenced corrosion and equipment failure are also there to contend with [5]. The processes involved in removing large deposits of sand have also been found to be time consuming. These and other attendant problems concerned with cost of repairs, operational safety and pollution, all aid in drawing the problem to global attention [2]. Hence, the need for studies on the subject matter for elaborate understanding and prediction of sand transport in multiphase flow (involving two or more distinct phases such as gas, oil and water).

An important parameter which can be applied in the evaluation of sand transport in multiphase flows is minimum transport condition (MTC), defined as the minimum average fluid velocity required to prevent bed formation which occurs as a result deposition of sand particles [2]. This according to Thomas [6] is the mean stream velocity required to prevent the accumulation of a layer of sliding sand particles at the bottom of a horizontal pipe. MTC concept is based on the principle that the sand particles in pipelines will not lose their ability to be transported in a fluid since they are fully suspended therein [2,6–8]. Other terms used to describe MTC are critical deposition velocity (CDV), critical transport fluid velocity (CTFV) and critical foam velocity (CFV) [2,9].

In sand resistant production systems, it is of great necessity knowing the actual value of sand MTC in pipelines to prevent sand bed formation [4], and predict objectively the changes that may have occurred and how often pipelines need to be dredged to prevent the havoc associated with blockage and abrasion [10]. Sand MTC in pipeline multiphase flow is dependent on several conditions such as sand particle size, sand concentration, pipe diameter, pipe inclination and fluid viscosity [1]. The high variability of these parameters has made the prediction of sand transport more tasking [11]. The dispersed distribution of sand transport in pipelines is also a militating factor against sand transport estimations [12].

Many of the models which have been developed for this purpose have proven to be a far cry from what is required for the knowledge of sand transport processes [10,13–17]. For instance, Wicks [13] developed correlations on sand transport in which only high solids concentration were considered for analysis. These correlations cannot be applied in the offshore environments where sand concentration was estimated to be between 5 to 40 lb of sand per 1000bbl of liquid [4]. Angelson *et al.* [14] improved on the model by extending it to two-phase flow and the only parameters considered were liquid velocity and hydraulic diameter. Imprecision resulted from the multiphase flow model due to incoherence between experimental data and the model. A general correlation for critical mixture velocity of multiphase flow was also formulated by Salama [15] as shown in **Equation 1** involving various experimentally determined theoretical parameters which cannot be adequately measured.

$$U_{M,C} = U_{SL} + U_{SG} = \left(\frac{U_{SL}}{U_M}\right)^{0.04} d_p{}^{0.17} v^{-0.09} (s-1)^{0.55} D^{0.47} \quad (1)$$

An empirical model for CDV prediction was put forward by Kökpinar and Göğüş [16] by assuming critical velocity as a function of the parameters given in **Equation 2**.

$$\frac{V_c}{\sqrt{gD}} = 0.055\left(\frac{d_p}{D}\right)^{-0.6} C_v{}^{0.27}(s-1)^{0.07}\left(\frac{\rho_1 u_t d_p}{\mu_1}\right)^{0.3} \quad (2)$$

A mechanistic model for CDV (**Equation 3**) was proposed by Al-Mutahar [17] based on turbulent theory and force balance. Estimation of turbulent velocity fluctuations generated by liquid flow and that required to suspend particles as well as assumptions of equality of the required and produced turbulent velocity fluctuations were made.

$$V_c = 5.66\left[f(C_v)\sqrt{d_p}\,g(s-1)\right]^{8/7}\left(\frac{D\rho_1}{\mu_1}\right)^{1/7}\left(\frac{1}{\Omega}\right)^{8/7} \quad (3)$$

where $\Omega = (1+3.64C_v)^{-1}$ for concentrations > 1%; $\Omega = 0.5\,(1+3.64C_v)^{-1}$ for concentrations < 1%

Yan [1] also developed a theoretical correlation for sand MTC as shown in **Equations (4-6)** for single phase flow.

$$u_o = \left[100u_t\left(\frac{v_l}{d_p}\right)^{2.71}\right]^{0.269} \quad (4)$$

$$u_c = u_o + 0.092\,C_v{}^{0.271} \quad \text{for} \quad 0.00000538 \le C_v \le 0.3\frac{\text{v}}{\text{v}} \quad (5)$$

The fanning factor can be obtained by applying **Equation 7** which was proposed by Chen [18].

$$u_c = \left(\frac{f}{2}\right)^{0.5} \times MTC \quad (6)$$

$$\frac{1}{\sqrt{f}} = -4\log\left[0.2698\left(\frac{\varepsilon}{D}\right) - \frac{5.0452}{Re}\log\left(0.3539\left(\frac{\varepsilon}{D}\right)^{1.1098} + \frac{5.8506}{Re^{0.8981}}\right)\right] \quad (7)$$

Apart from the inconsistency caused by the assumptions, the parameters involved in these correlations are those which cannot but be experimentally determined in accordance with proven mechanistic models. This is one shortcoming that the present study is intended to resolve with the development of an empirical model which will factor in the operational parameters directly affecting sand MTC, and by extension sand transport in pipeline multiphase flow.

In this study, RSM was used to establish the relationship between the response and operational parameters because it is effective in optimizing the response function and predicting future responses after it has developed a regression model statistically from appropriate experimental data [19]. From the several design types available in RSM: Box–Behnken, central-composite, one-factor, optimal and historical data, historical data is the preferred choice for this study as it can accommodate all available data into a blank design layout from an already conducted experiment [20]. Also, it is suitable for conducting multi-factor experiments because it provides information on the influence of factor interactions [21].

Liquid viscosity, pipe diameter and sand concentration have been recognized as important parameters influencing sand MTC in pipeline multiphase flow as reported by Yan [1]. It is the aim of this study to develop an empirical model that will explain explicitly the effect of the interactions of these parameters on sand MTC in pipeline multiphase flow, a feat which has not been reached due to insufficient data, and to improve upon the approach of Yan [1] involving experimental determination of MTC by visual observations and assumptions. The optimum operating conditions will also be evaluated from optimization of the response.

2. Methodology

2.1. Experimental design and model development

RSM of Design Expert software version 6.0.8 (Stat-Ease Inc., Minneapolis, USA) was used in this study. Historical data experimental design, with categorical factor of 0, was employed in modelling and optimizing sand MTC. The three parameters: liquid viscosity, pipe diameter and sand concentration, which are conditions affecting MTC, were operated within two ranges (minimum (-1) and maximum (+1)). The lowest and the highest levels of the variables were: liquid viscosity, 1 and 340 cP; pipe diameter, 0.0776 and 0.1 m; sand concentration, 50 and 200 lb/1000bbl. All experimental data sets of a total of 12 runs were used as the design points for modelling and optimizing the level of chosen variables from the experimental results of Yan [1].

The experimental data of the historical design experiment can be represented in the general form of the two-factor interaction (2FI) model as shown in **Equation 8**, to develop an empirical model which will be used to analyse the effect of factor interactions.

$$Y = b_o + \sum b_i X_i + \sum b_{ij} X_i X_j + e_i \qquad (8)$$

(after Bradley [19]; Ahmad *et al.,* [22]; Fakhri and Adami,[23]).

where Y is the predicted response; n is the number of factors; X_i and X_j are the coded variables; b_o is the constant coefficient; b_i and b_{ij} are the first-order and interaction coefficients, respectively; i and j are the index numbers for factors; and e_i is the residual error.

The operating parameters, their designated symbols, response and range of conditions are presented in Table 1.

Table 1. Design summary

Operating Parameters	Symbols	Ranges	Low Coded	High Coded
Liquid Viscosity (cP)	A	1 - 340	-1	+1
Pipe Diameter (m)	B	0.0776 – 0.10	-1	+1
Sand Concentration (lb/1000bbl)	C	50 - 200	-1	+1
Response	Symbol	Analysis	Minimum	Maximum
MTC (m/s)	Y1	Polynomial (2FI)	0.070	0.80

The validity of the polynomial model was expressed by the coefficient of determination, R^2 and coefficient of adjusted determination, Adj-R^2 while the statistical significance was verified with the F-test and the adequate precision ratio.

2.2. Optimization of sand MTC and operational parameters

Numerical optimization of the model in Equation (2) was done using the Design Expert software to determine the liquid viscosity, pipe diameter and sand concentration at which the sand MTC of fluid was at maximum. The following steps were taken prior to the optimization in order to identify the criteria of the numerical optimization. First, the goal factors for the operational parameters were set to ''is in range'' with the exception of liquid viscosity (105 and 340 cP) in consistency with the viscosity of oil [1], while that of sand MTC was set to "minimum". The lower limit of the response was the minimum response obtained from the interactions of the parameters considered.

3. Results and discussion

3.1. Model fitting

The effects of the different process parameters on the value of MTC were investigated. This work contributes immensely to existing knowledge since little or no work has been done on the development of an empirical model and optimization of sand MTC in pipeline multiphase flow. The historical data RSM design and the response for this study can be found in **Table 2**.

Table 2. Historical Data Experimental Design of the Independent Variables and the observed values for the response

Std	Run	Experimental Variables			Response	
		Liquid viscosity (cP)	Pipe diameter (m)	Sand concen-tration (lb/bbl)	Actual MTC (m/s)	Predicted MTC (m/s)
1	1	1	0.1000	50	0.600	0.630
12	2	7	0.1000	50	0.700	0.670
5	3	20	0.1000	50	0.750	0.750
10	4	105	0.0776	50	0.350	0.350
9	5	200	0.0776	50	0.250	0.240
4	6	340	0.0776	50	0.070	0.075
8	7	1	0.1000	200	0.700	0.700
2	8	7	0.1000	200	0.750	0.740
6	9	20	0.1000	200	0.800	0.820
3	10	105	0.0776	200	0.450	0.430
7	11	200	0.0776	200	0.300	0.330
11	12	340	0.0776	200	0.200	0.190

Polynomial regression analysis was performed on the response to determine the coefficients of the model terms. Model reduction by manual exclusion of larger insignificant terms, were not performed since bulk of the model terms were significant. The predicted response of sand MTC is expressed by **Equation 9** in terms of actual factors.

$$MTC = -0.048324 - 0.026382 * Liquid\ Viscosity + 6.53261 * Pipe\ Diameter + 0.000340814 * Sand\ Concentration + 0.324 * Liquid\ Viscosity * Pipe\ Diameter + 0.000000967431 * Liquid\ Viscosity * Sand\ Concentration + 0.000946007 * Pipe\ Diameter * Sand\ Concentration \quad (9)$$

The empirical model includes all the factors in consideration, thereby eliminating the need for experimental determination of theoretical parameters required by mechanistic models.

3.2. Analysis of variance (ANOVA) and statistical significance of the model

For the optimization of MTC, Analysis of Variance (ANOVA) values were obtained for the 2FI regression model in Equation 9. The ANOVA results derived from the historical data utilized for this study are listed in Table 3. The p (or prob) values depicted the significance of each coefficient as well the interaction effectiveness between each independent variable. The p-value < .0001 and the model F-value of 139.38 (a large value occurring due to noise) for the 2FI model, suggests that the regression model is statistically significant. The significance of the regression coefficients is also depicted in Table 3. P-values < .05 indicate that the model terms are significant at 95% confidence level.

Table 3. ANOVA for Response Surface 2FI Model

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob > F	Remark
Model	0.702666	6	0.117111	139.3804	< 0.0001	significant
A	0.009451	1	0.009451	11.24802	0.0202	
B	0.027774	1	0.027774	33.05528	0.0022	
C	0.013606	1	0.013606	16.1933	0.0101	
AB	0.019742	1	0.019742	23.49629	0.0047	
AC	0.000296	1	0.000296	0.352615	0.5785	
BC	2.33E-06	1	2.33E-06	0.002771	0.9601	
Residual	0.004201	5	0.00084			
Cor Total	0.706867	11				

From the ANOVA, it can be observed that four (4) of the six (6) model terms (A, B, C and AB) are significant. The significant model terms have synergistic effect on the regression model while insignificant terms have antagonistic effect. Therefore, model factors A, B, C and AB positively contribute to the model equation while AC and BC have negative impact on the developed model. The most influential model parameter was B because it had the least p-value.

3.3. Validation of the model

Since adequate precision measures the signal to noise ratio and a ratio value greater than 4 is desirable, the 2FI model of liquid velocity at sand MTC with adequate precision ratio of 33.505 indicates an adequate signal. The 2FI regression model fitting was regulated by the coefficient of determination, R^2 which gave a high value of 0.9941 for the liquid velocity at sand MTC from the ANOVA results. A reasonable agreement of the R^2 with the adjusted coefficient of determination, Adj-R^2, is of great importance. The value of Adj-R^2 obtained was 0.9869. Therefore, the proximity of the R^2 and Adj-R^2 value to 1.0 indicates a very high correlation between the experimental and the predicted values of the liquid velocity at sand MTC. From the foregoing, the 2FI regression model presents an explicit explanation of the relationship between the independent factors and response.

3.4. Verification of model adequacy

The adequacy of the regression model was also ascertained between the experimental data and the model response with the diagnostic plot shown in Figure 1.

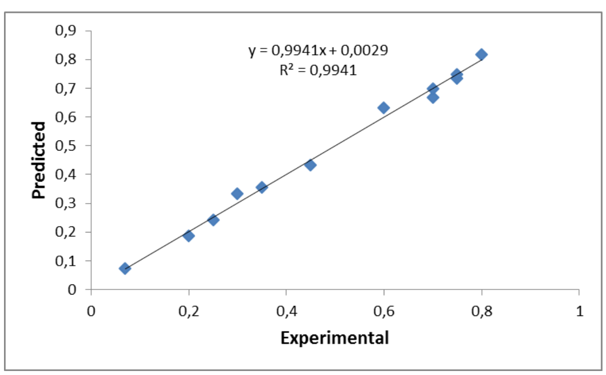

Figure 1. Cross plot between the Experimental and Predicted Values.

It can be observed that the 2FI regression model fits realistically, thereby adequately expressing the experimental range studied. The actual value of sand MTC velocity represents the measured result for each experimental run while the predicted value is evaluated from the independent variables in the regression model.

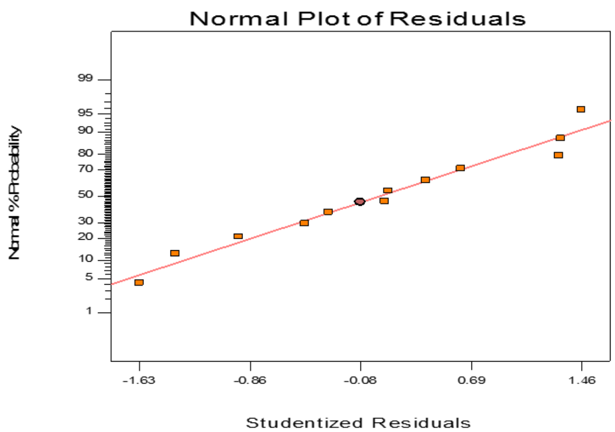

Figure 2. Normal plot of residuals for the model.

The normal plot of residuals depicts the graphical analysis of the model as exhibited by Figure 2. It is obvious that the residuals reflect a normal distribution since virtually all the points follow a straight-line curve. It is also revealed that no further improvement can be done to the model by making changes to the response because the data points are scattered and do not exhibit "S-shaped" curve [20]. The graphs and tables thereby suggest that the model in Equation 9 can be regarded as the best possible model of the historical data RSM design of sand MTC in pipeline multiphase flow. Therefore, these shall be utilized in deriving the optimum values of the operational parameters.

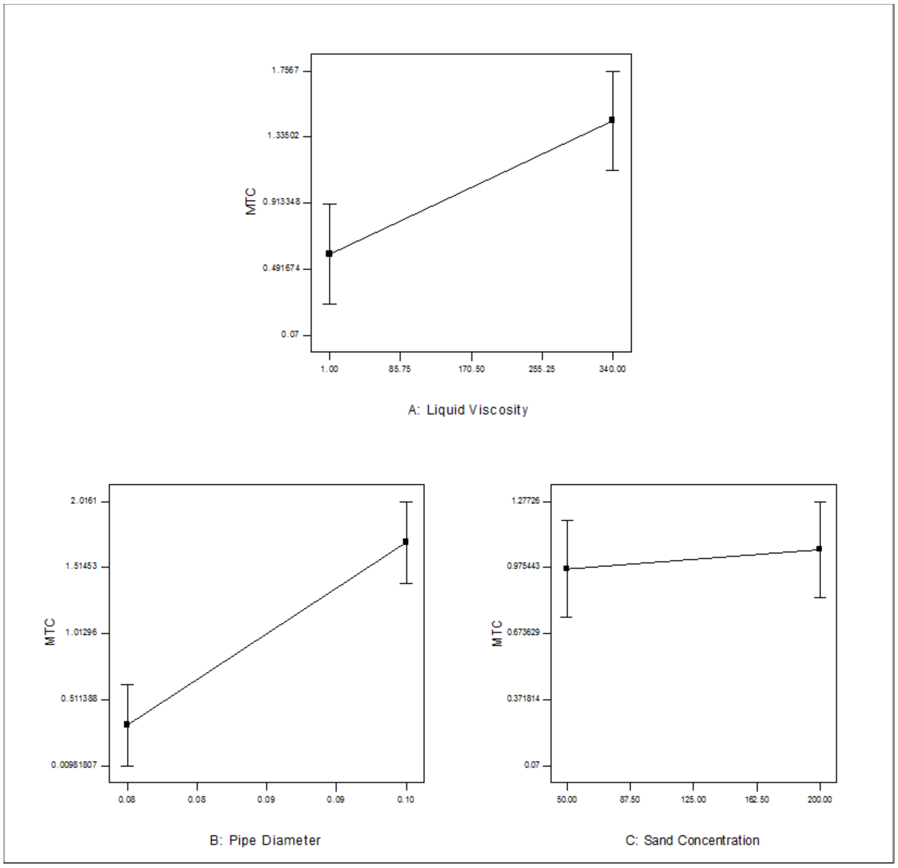

Figure 3. One factor plots.

The individual effects of each operational parameter: liquid viscosity, pipe diameter and sand concentration on the MTC in multiphase pipelines are presented in Figure 3 (i-iv). Figure 3 (i) shows the effect of liquid viscosity on MTC at constant pipe diameter and sand concentration. MTC increased slightly from 0.5874 to 1.4385 m/s with increase in liquid viscosity from 1 to 340 cP, reflecting a direct relationship. Figure 3 (ii) depicts the effect of pipe diameter on MTC at constant liquid viscosity and sand concentration. There was a more pronounced increase in MTC from 0.3198 to 1.7062 m/s when pipe diameter increased from 0.0776 to 0.10 m. Figure 3 (iii) illustrates the effect of sand concentration on MTC at constant liquid viscosity and pipe diameter. The MTC increased slightly from 0.9687 to 1.0572 m/s when sand concentration increased from 50 to 200 lb/1000bbl, depicting the least significant effect on the response. Therefore, the three parameters have a synergistic effect with pipe diameter indicating the greatest main factor effect on MTC in multiphase flow pipelines.

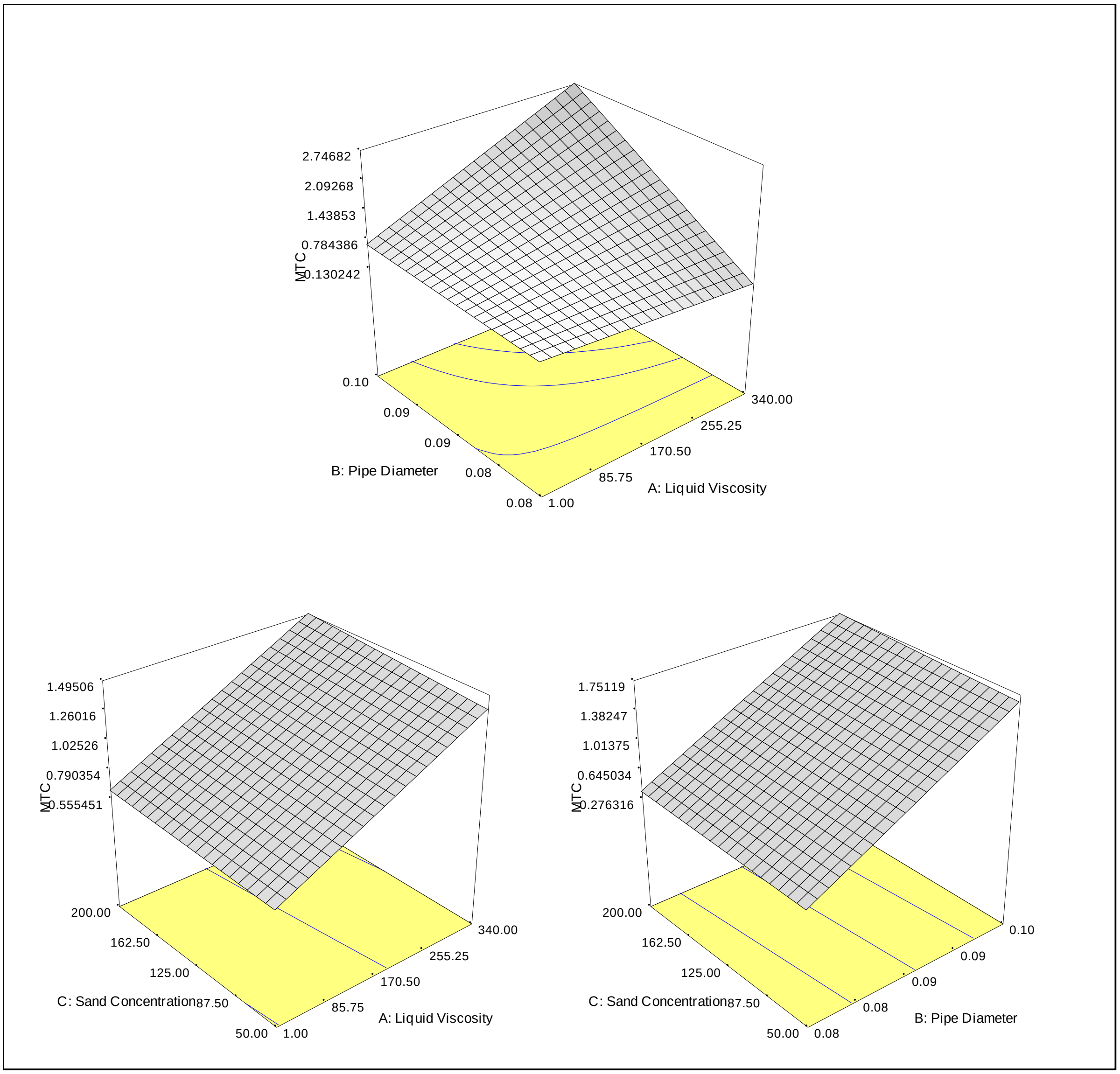

Figure 4. 3D Response surface plots

In this paper, the three dimensional (3D) plots depicted by Figure 4 (i-iii) were studied to investigate the behaviour of the sand MTC from the interactions of the three operating variables: liquid viscosity, pipe diameter and sand concentration. Two operating variables were analysed in each case while the other variable was kept constant.

The 3D plot showing the effect of the combination of liquid viscosity and pipe diameter on sand MTC when sand concentration was kept constant is presented by Figure 4 (i). The sand MTC velocity increased from 0.67 to 2.75 m/s when liquid viscosity increased from 1 to 340 cP with pipe diameter of 0.1 m. There was however, a slight decrease in sand MTC velocity from 0.51 to 0.13 m/s with equivalent increment in liquid viscosity when a smaller pipe of diameter 0.0776 m was used. These were observed at constant sand concentration of 125 lb/1000bbl. The increase in sand MTC of fluids was more prominent at high liquid viscosity with decrease in pipe diameter than it was at low liquid viscosity.

Figure 4 (ii) depicts the combined effect of liquid viscosity and sand concentration at constant pipe diameter on sand MTC. It is clearly indicated at constant pipe diameter that at sand concentration of 200 lb/bbl, there was a continuous increase in sand MTC from 0.62 to 1.50 m/s when liquid viscosity increased from 1 to 340 cP. A similar trend was observed for sand concentration of 50 lb/bbl with the same increase in liquid viscosity as sand MTC increased from 0.56 to 1.38 m/s. The increase in MTC experienced with increase in liquid viscosity was more appreciable than that experienced with increase in sand concentration, thereby making the effect of latter rather insignificant.

The combined effect of pipe diameter and sand concentration on velocity of sand at MTC when liquid viscosity was kept constant is depicted by the 3D plot shown in Figure 4 (iii). The sand MTC increased from 0.36 to 1.75 m/s at sand concentration of 200 lb/bbl when the pipe diameter was increased from 0.0776 to 0.1 m. The observations at sand concentration of 50 lb/bbl was similar as sand MTC velocity increased from 0.28 to 1.66 m/s when the same increase in pipe diameter was maintained. The effect of increasing pipe diameter in increasing sand MTC of fluids overwhelms that of sand concentration.

It can be inferred from these plots that liquid viscosity and pipe diameter are the most significant parameters influencing MTC of fluids in sand transport multiphase pipelines. The effect of sand concentration is greatly masked and as such can be considered the least significant.

3.5. Validation of model optimization

Figure 5 illustrates the predicted optimum conditions and the response studied in this paper. The predicted optimum operating parameters influencing sand MTC was estimated to be liquid viscosity (335.63 cP), pipe diameter (0.08 m) and sand concentration (115.61 lb/1000bbl). At these optimum conditions, the corresponding predicted volumetric mass transfer coefficient was found to be 0.130242 m/s.

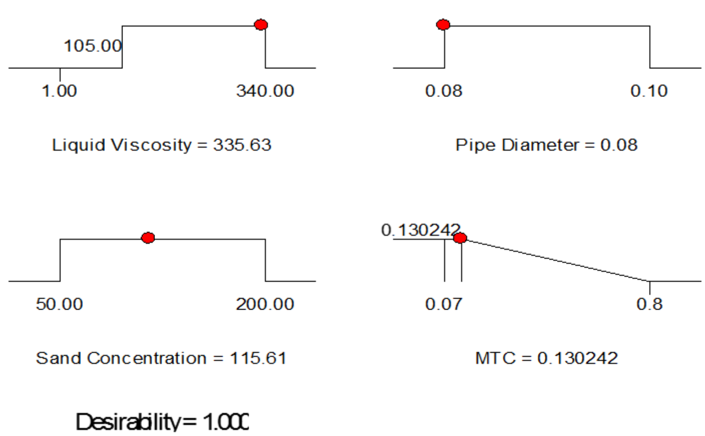

Figure 5. Optimum conditions and response

Experimentally, liquid viscosity (340 cP), pipe diameter (0.08 m) and sand concentration (125 lb/1000bbl) were the values of the operating parameters whose interactive effect gave minimum sand MTC as 0.130242 m/s. Thus, it is evident that the historical data RSM design is an efficient statistical technique for predicting the optimum operating variables for the minimization of sand MTC in pipeline multiphase flow by incorporating all factors under consideration.

4. Conclusion

This study revealed the effectiveness of RSM to successfully develop a suitable empirical model for the prediction of sand MTC in the investigation of sand transport in multiphase pipelines. This model has an advantage over the previously developed mechanistic models because it directly includes the factors under consideration with the aim of studying their interactive effects in contrast to the latter which requires assumptions and experimental determination of factors which only gives estimations of MTC and hence sand transport in multiphase pipelines. The closeness of R^2 (0.9941) and Adj-R^2 (0.9869) to 1.0 proved that there was coherence between the experimental and predicted response. 3D response surface plots were employed in explaining the effects of interaction of the operating parameters considered in this study and they revealed that liquid viscosity and pipe diameter are the most significant parameters affecting the response. Numerical optimization showed that the predicted optimum operating parameters observed at liquid viscosity (335.63 cP), pipeline diameter (0.08 m) and sand concentration (115.61 lb/1000bbl) to achieve minimum MTC of 0.130242 m/s were close to the experimental optimum conditions of 340 cP liquid viscosity, 0.08 m pipeline diameter, 125 lb/1000bbl sand concentrations and 0.130242 m/s MTC. Sand MTC minimization is vital for reduction in energy requirement. It can thus be concluded that historical data RSM is a reliable statistical technique for the prediction and optimization of sand MTC in pipeline multiphase flow and that estimation of sand MTC under the conditions considered is crucial for oil pipeline design to provide quality assurance for sand transport during operation.

Nomenclature

C_v	*Sand volume fraction*	*v/v*
d_p	*Particle diameter*	*microns*
D	*Pipe diameter*	*m*
ε	*Pipe roughness*	*m*
f	*Friction factor*	
g	*Gravitational acceleration*	*m/s²* → m/s^2
Re	*Reynolds number*	
s	*Ratio of particle to carrier fluid density*	
u_o	*Friction velocity at minimum transport condition for infinite dilution*	*m/s*
u_t	*Terminal settling velocity*	*m/s*
u_c	*Friction velocity at minimum transport condition*	*m/s*
ρ_1	*Liquid density*	kg/m^3
U_M	*Mixture velocity*	*m/s*
$U_{M,C}$	*Critical mixture velocity*	*m/s*
U_{SG}	*Superficial gas velocity*	*m/s*
U_{SL}	*Superficial liquid velocity*	*m/s*
μ_1	*Liquid dynamic viscosity*	*Pas*
v	*Liquid velocity*	*m/s*
v_l	*Liquid kinematic viscosity*	m^2/s
V_c	*Critical Transport Velocity*	*m/s*

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