Optimization of Cyclic Steam Stimulation Process Using Response Surface Methodology

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ABSTRACT

Heavy oil has characteristics such as API gravity 10-20 and high viscosity (100-10,000 cp) at reservoir temperature. Several methods have been successfully applied to produce these reserves, such as cyclic steam stimulation (CSS). Cyclic steam stimulation is a thermal injection method that aims to heat the oil around production wells. This paper presents the investigation regarding CSS application in heavy oil using Response Surface Methodology. Several scenarios were done by varying the operating conditions to obtain the most realistic results and also evaluating the factors that most influence the success of CSS process. Optimization is performed to find the maximum recovery factor (RF) value and minimum steam oil cumulative ratio (CSOR). The operating parameters used are CSS cycle, steam injection rate, and steam quality. Then statistical modeling is carried out to test the most important parameters affecting RF and CSOR for 10 years. The simulation results show that the CSS cycle, steam injection rate, and steam quality affect the RF and CSOR. The maximum RF results with the minimum CSOR were obtained at 39 cycles, an injection rate of 300 bbl/day, and a steam quality of 0.9 with an RF and CSOR value is 24.102% and 3.5129 respectively.

Keywords: cyclic steam stimulation; heavy oil; recovery factor; response surface methodology; steam oil ratio cumulative

I. INTRODUCTION

Oil reserves in the world contain large amounts of heavy oil (Zhu, 2011) which have characteristics such as API gravity 10 - 20 and high viscosity (100 cp - 10,000 cp) at reservoir temperature. Several methods have been successfully applied to produce these reserves, one of which is cyclic steam stimulation (CSS).

Cyclic steam stimulation is one of the Thermal Injection methods where steam with a high temperature is injected into the reservoir periodically, there are three phases, namely the injection phase, the soaking phase, and the production phase. High temperatures can cause the reservoir temperature to rise and the viscosity of the oil to decrease so that the mobility of the oil will be higher and it is easier to flow to the surface.

Planning a cyclic steam stimulation is needed to obtain optimal production. In optimizing cyclic steam stimulation, several parameters are very important. These parameters are the injection cycle (cycle), the amount of steam injection (rate), and the steam quality which must be well calculated to achieve successful operation.

The optimization is done by using the simulation method. The simulation is carried out on a simple model that represents the ANR-well so that the model has the same value or fit the X-Field. The simulation will be carried out on the well in X-Field using CMG software which is expected to provide information about the increase in recovery in X-Field. X-Field itself is located in central Sumatra, Indonesia, and has a reservoir containing heavy oil.

Optimization planning for cyclic steam stimulation in this study uses the Response Surface Methodology. By using this method, several scenarios are carried out by varying the operating conditions to obtain the most realistic results and also evaluating the factors that most influence the Recovery Factor.

II. METHODS

The Response Surface is an advanced experimental design (DOE) techniques that help better understand and optimize response. Response Surface Methodology is often used to refine a model after determining important factors. Response Surface uses the addition of a square term that models curvature in the response, making it useful for understanding or mapping the response surface area, finding variable levels that optimize the response, and selecting operating conditions to meet specifications. This research uses four phases:

2.1. Planning Phase

At this phase, the activities carried out are planning or determining the fixed/dependent/response variables and the independent variables. The response variables consist of recovery factor (RF) and cumulative steam oil ratio (CSOR), while the independent variables consist of CSS cycle, injection rate, and steam quality. After knowing the variables, determine the value range of each independent variable by determining the lowest value (low level), middle value (center level), and the highest value (high level). And determine the injection period for each cycle. The results of the design are inputted into the Minitab software to form a response surface design consisting of several scenarios that contain a combination of each independent variable and look for the results of the RF and CSOR values in each scenario.

2.2. Model Analysis Phase

The response variables obtained were then analyzed using Minitab software, to obtain a Coefficient Table, ANOVA Table, Summary Model Table, Pareto Diagram, Regression Equation, and Residual Plot. There are four main analyzes carried out, the first is analyzing the most contributing terms which can be analyzed through the Pareto Diagram, where the greatest value and passing the reference line is the most contributing term. Second, analyzing the relationship between terms and responses which can be analyzed through the P-value in the Coefficient Table and ANOVA Table, where if the P-value is greater than the significance level (0.05), then the term and response are statistically significant, and vice versa when the P value less than the significance level (0.05). Third, analyzing the relationship between the model and the data that can be analyzed through the Model Summary Table, where when the S value is getting smaller and the R-sq value is getting bigger, the better the model represents the data and it is better at predicting responses. Fourth, analyzing the adequacy of the model to meet the analysis assumptions that can be analyzed through the Residual Plot, where the residual plot contains four graphs, namely the Normal Probability Plot, Residual versus Order, Histogram, and Residual versus Fits. To fulfill the assumptions of the analysis, the four graphs must show a graph that is normally distributed.

2.3. Optimization Phase

After the model is analyzed and it feels good enough. Then carry out the optimization stage. Optimization is carried out in three ways, which is contour plot analysis, surface plot analysis, and using response optimizer that forms a new scenario, called the optimum scenario. The first analysis is to see the results of the contour plot and surface plot, to see the optimum value, and see the mapping of the surface area of the response. After being analyzed and not getting a definite value, then analyzed using the response optimizer. The response optimizer itself is a sub-menu in Minitab that functions to perform optimization by paying attention to the curvature of each independent variable with a response that will get a definite value at the optimum response conditions and predict the response value obtained and its range.

2.4. Verification Phase

Perform the verification phase after obtaining the optimum scenario from the optimization phase to determine the level of optimization prediction accuracy and get the best optimum scenario.

III. RESULTS AND DISCUSSION

3.1. Description of Reservoir Model

The software used in reservoir modeling is CMG STARS 2015 which is included in the thermal simulation. This software is widely used for the study of hot steam injection as an advanced oil recovery method (Enhanced Oil Recovery). The reservoir model is ideally made without any fractures or folds. There is no gas cap or aquifer in the model. Porosity, permeability, oil saturation, and other reservoir parameters are assumed to be homogeneous in all reservoir models and there is no history matching process due to the lack of available data. Reservoir characteristics data can be seen in **Table 1**.

Table 1. ANR-Well Reservoir Properties

Parameters	Value
Top grid depth, ft	467
Reservoir pressure, psi	200
Reservoir temperature, oF	100
Net pay thickness, ft	59
Porosity, %	0,4
Permeability, mD	1126
Effective water saturation	0,45
Rock compressibility, 1/psi	58x10-6
Oil density, lb/cuft	58,9
Oil FVF, RB/STB	1,067

GOR, SCF/STB	19,2
Oil molecular weight, lb/lbmole	283
Gas molecular weight, lb/lbmole	2,38
Oil mole fraction	0,95
Gas mole fraction	0,05
Oil critical pressure, psia	774,4
Oil critical temperature, 0F	248,6
Gas critical pressure, psia	1014,09
Gas critical temperature, 0F	-60,31
Oil heat capacity, BTU/cuft-0F	0,526
Reservoir Thermal Expansion, Vol/vol/0F	$4x10^{-4}$
Overburden heat capacity, BTU/cuft-°F	38,4
Underburden heat capacity, BTU/cuft-°F	38,4
Overburden heat conductivity, Btu/ft day °F	35
Underburden heat conductivity, Btu/ft day °F	35

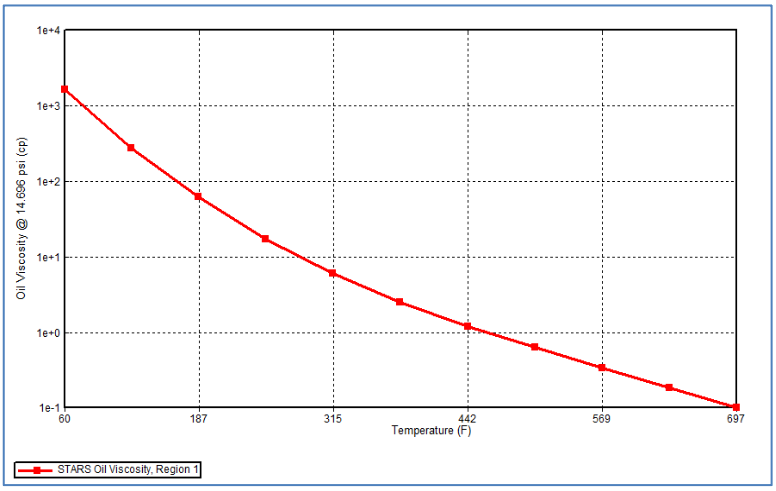


Figure 1. Oil Viscosity vs Temperature

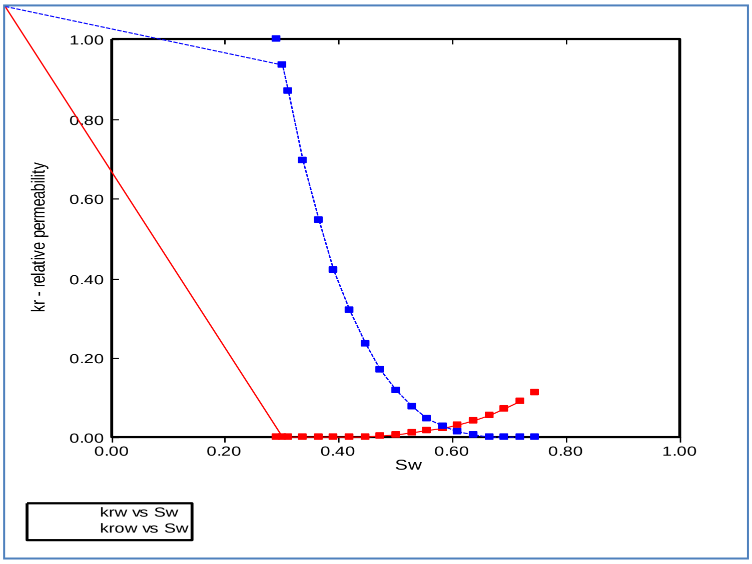


Figure 2. Relative Permeability Curve

Table 2. ANR-Well Reservoir Properties

Parameters	Minimum	Center	Maximum
CSS cycle, times	20	30	40
Steam injection rate, bbl/day	200	250	300
Steam quality, fraction	0.5	0.7	0.9

The inherent assumptions include homogeneous reservoir, no-flow boundary, the same conductivity, and heat capacity in over-burden and under-burden layers. There are no gas cap and bottom water drive. The geomechanically effects such as dilation related to the pressure or temperature are ignored in this model. The rock properties and fluid properties are assumed to be homogeneous in the whole reservoir. Oil column thickness is constant for all the layers. The total grid number is 9 x 1 x 12 (i,j,k) with a radius of 250 m. the temperature of the steam is 550 oF. There are 18 scenarios with different parameters are generated by using experimental design. The RF and CSOR of each scenario will be calculated.

3.2. Response Surface Methodology Model

A total of 18 scenarios were formed from variations in operating conditions using Box-Behnken Design. Running has been done and the results of the RF and CSOR response variables can be seen in Table 3. Then the data is processed using Minitab 19 software to validate the model and determine the regression equation.

Table 3. RF and CSOR for each scenarios

Run	Cycle	Rate	Quality	RF	CSOR
1	20	200	0,7	14,2824	3,49294
2	40	200	0,7	17,5216	3,67472
3	20	300	0,7	14,6423	3,59766
4	40	300	0,7	22,6731	3,76157
5	20	250	0,5	14,0116	3,81091
6	40	250	0,5	17,6467	4,37180
7	20	250	0,9	15,2837	3,18636
8	40	250	0,9	23,3888	3,18747
9	30	200	0,5	17,5776	4,61063
10	30	300	0,5	21,1791	4,94638
11	30	200	0,9	22,9302	3,41438
12	30	300	0,9	27,1584	3,51284
13	30	250	0,7	22,3974	4,14111
14	30	250	0,7	22,3974	4,14111
15	20	200	0,5	13,6012	3,76973
16	40	300	0,9	25,5956	3,21523
17	20	300	0,9	15,4160	3,19234
18	40	200	0,5	15,7071	4,14818

A summary of the results of the recovery factor and cumulative steam oil ratio obtained through the CMG 15 simulator can be seen in **Table 3**. At 20 cycles, the RF obtained ranged from 13.6012 - 15.416%, CSOR was around 3.18636 - 3.81091. For 30 cycles, the RF obtained ranged from 17.5776 - 27.1584%, CSOR was around 3.41438 - 4.94638. For 40 cycles, the RF obtained ranged from 15.7071 - 25.5956%, CSOR was around 3.18747 - 4.3718. The highest RF price is 27.1584% at 30 cycles, rate 300 bbl/day, steam quality 0.9. The lowest CSOR price is 3.18636 at 20 cycles, rate 250 bbl/day, steam quality 0.9.

3.3. Result of Model Analysis

To validate the model, validation was carried out through graphical and numerical methods using Tukey's test and ANOVA. The coefficient table, ANOVA table, model summary table, Pareto chart, and residual plot are obtained for each response.

Table 4. Coefficient Table

Term	RF				CSOR			
	Coef	T-Value	P-Value	VIF	Coef	T-Value	P-Value	VIF
Constant	22,371	41,860	0,000		4,1364	51,5100	0,0000	
Cycle	2,941	12,400	0,000	1,00	0,1091	3,0600	0,0160	1,00
Injection Rate	1,409	5,600	0,001	1,12	0,1030	2,7200	0,0260	1,12
Steam Quality	2,034	8,090	0,000	1,12	-0,5301	-14,0200	0,0000	1,12
Cycle*Cycle	-4,853	-11,380	0,000	1,08	-0,4921	-7,6800	0,0000	1,08
Injection Rate*Injection Rate	-0,225	-0,530	0,612	1,08	-0,0102	-0,1600	0,8770	1,08
Steam Quality*Steam Quality	0,078	0,180	0,859	1,08	-0,0028	-0,0400	0,9660	1,08
Cycle*Injection Rate	1,099	3,280	0,011	1,33	0,0140	0,2800	0,7880	1,33
Cycle*Steam Quality	1,019	3,040	0,016	1,33	-0,1214	-2,4100	0,0430	1,33
Injection Rate*Steam Quality	0,183	0,530	0,607	1,23	-0,0546	-1,0600	0,3190	1,23

Table 5. Result of ANOVA Test

Term	DF	RF		CSOR	
		F-Value	P-Value	F-Value	P-Value
Model	9	52,570	0,000	31,9000	0,0000
Linear	3	98,870	0,000	70,1100	0,0000
Cycle	1	153,790	0,000	9,3700	0,0160
Injection Rate	1	31,360	0,001	7,4200	0,0260
Steam Quality	1	65,400	0,000	196,6700	0,0000
Square	3	43,550	0,000	19,8000	0,0000
Cycle*Cycle	1	129,610	0,000	59,0300	0,0000
Injection Rate*Injection Rate	1	0,280	0,612	0,0300	0,8770
Steam Quality*Steam Quality	1	0,030	0,859	0,0000	0,9660
2-Way Interaction	3	13,380	0,002	2,6900	0,1170
Cycle*Injection Rate	1	10,730	0,011	0,0800	0,7880
Cycle*Steam Quality	1	9,220	0,016	5,8100	0,0430
Injection Rate*Steam Quality	1	0,290	0,607	1,1300	0,3190
Error	8				
Total	17				

Table 6. Model Summary Table

RF				CSOR			
S	R-sq	R-sq (adj)	R-sq (pred)	S	R-sq	R-sq (adj)	R-sq (pred)
0,821624	98,34%	96,47%	93,18%	0,123448	97,29%	94,24%	80,14%

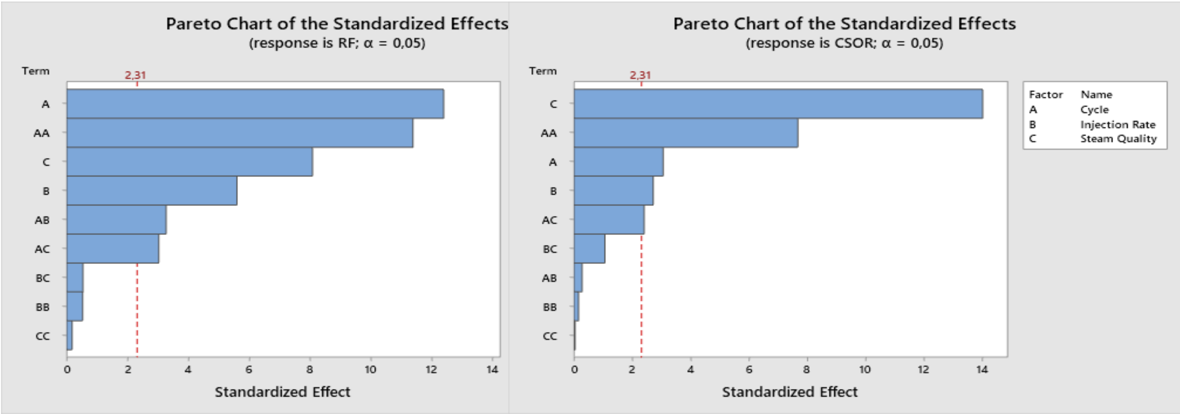


Figure 3. Pareto Chart

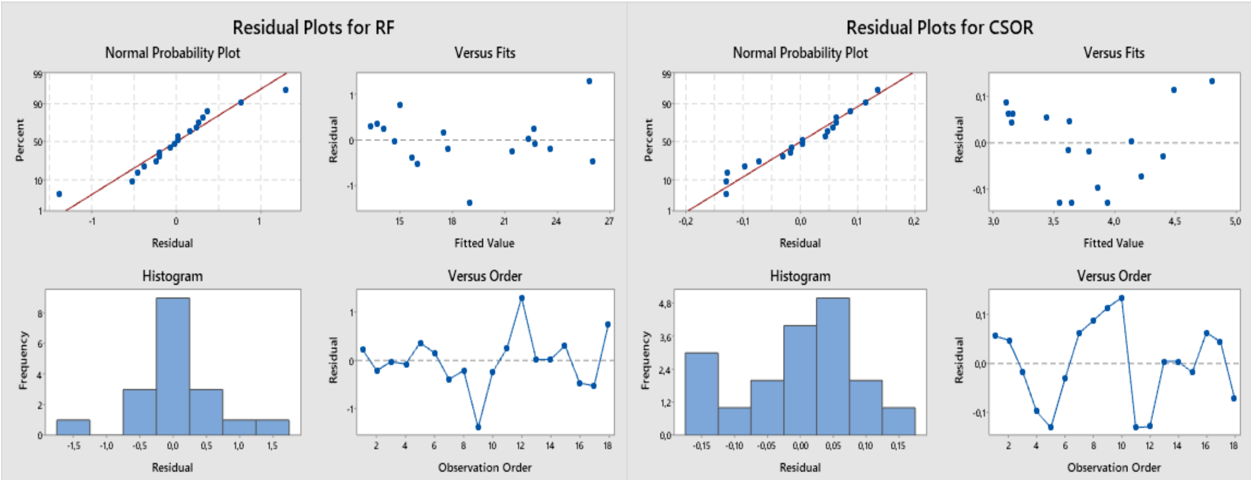


Figure 4. Residual Plot

In response surface design analysis, there are key results which are important factors in model analysis, the first is determining the terms that most contribute to response variations. This determination can be seen by looking at the Pareto chart in **Figure 3**. Based on the Pareto graph of the RF response can be seen in **Figure 3**, it can be seen that the terms that contribute the most in a sequence are cycle, square of cycles, steam quality, injection rate, interaction between cycle and injection rate, and interaction between cycle and steam quality because it passes through the standardized line which is 2.31. Based on the Pareto graph of the CSOR response can be seen in **Figure 3**, it can be seen that the terms that contribute the most in order are steam quality, square of cycles, cycle, injection rate, and the interaction between cycle and steam quality.

The second key result is the significance of the relationship between response and term. This relationship can be analyzed through the P-value in the coefficient table and the ANOVA table. Based on the Analysis of Variance (ANOVA) test for RF response can be seen in **Table 5**, regression model, cycle, injection rate, steam quality, square of cycles, and the interaction between cycle and injection rate, as well as interaction between cycles with steam quality have a significant effect on the obtained RF response ($P < 0.05$) at the 95% probability level. Whereas in the CSOR response, the effect is almost the same as RF, namely the regression model, cycle, injection rate, steam quality, square of cycles, and the interaction between cycle and steam quality has a significant effect on the obtained RF response ($P < 0.05$).

The third key result is determining how well the model fits the data by analyzing the S and R-sq values in the Model Summary Table can be seen in **Table 6**. The S value in the Model summary for the RF and CSOR responses is quite small, namely 0.821624 and 0.123448, respectively. The R-sq value in the RF and CSOR responses respectively is 98.34% and 97.29% which are quite high. So it can be concluded that the suitability of the model with the data is good.

The fourth key result is the adequacy of the model to meet the analytical assumptions which can be analyzed through the Normal Probability Plot, Residual versus fits Plot, and Residual versus Order Plot on the Residual Plot. To find out whether the model meets the assumptions of the analysis, the three parameters do not form patterns that can indicate that the model does not meet the assumptions of the analysis. The Normal probability plot for the RF response tends to form an inverted S curve and the CSOR is normally distributed, namely following a straight line can be seen in **Figure 4**. Residual versus fits for RF and CSOR responses are also normally distributed from a point spread without forming a pattern and the spread is not too far from zero. The residual versus order for the RF and CSOR responses is also normally distributed because the dots are scattered irregularly and do not form a pattern. So, it can be concluded that the model is sufficient to meet the assumptions of the analysis.

3.4. Accuracy Model

The relationship between the independent variables and the responses is constructed by using least square method. By using full quadratic model, the relationship between independent variable and responses can be described by:

$$RF = -18{,}6 + 2{,}3\,A - 0{,}0056\,B - 12{,}4\,C - 0{,}04853\,A*A - 0{,}00009\,B*B + 2\,C*C + 0{,}002198\,A*B + 0{,}509\,A*C + 0{,}0183\,B*C \quad (1)$$

$$CSOR = -1{,}59 + 0{,}3417\,A + 0{,}0071\,B + 0{,}63\,C - 0{,}004921\,A*A - 0{,}000004\,B*B - 0{,}07\,C*C + 0{,}000028\,A*B - 0{,}0607\,A*C - 0{,}00546\,B*C \quad (2)$$

Where:

RF = Recovery factor, %
CSOR = Steam Oil Ratio Cumulative, bbl/bbl
A = CSS cycle
B = Steam Injection Rate, bbl/day
C = Steam Quality, fraction

In order to validate the equation, the plot between observed values and predicted values are calculated by using the equation that can be seen in **Figure 5** and **Figure 6**.

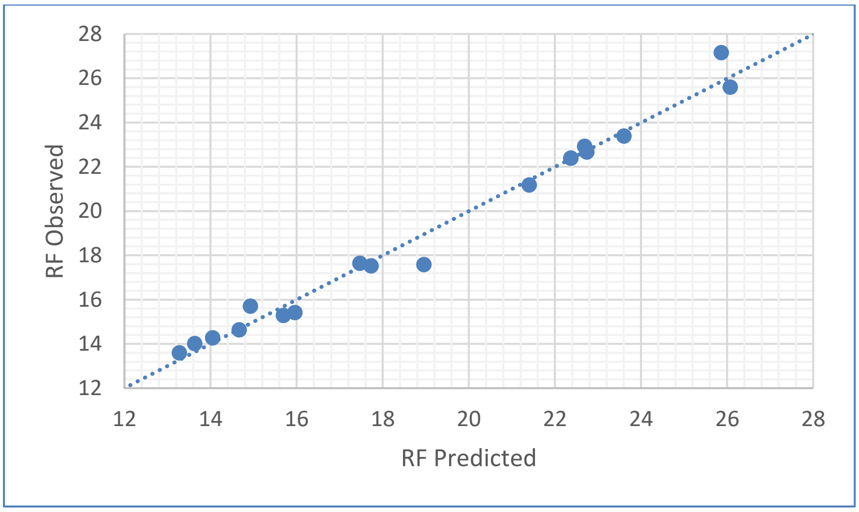


Figure 5. The relationship between RF observed and predicted

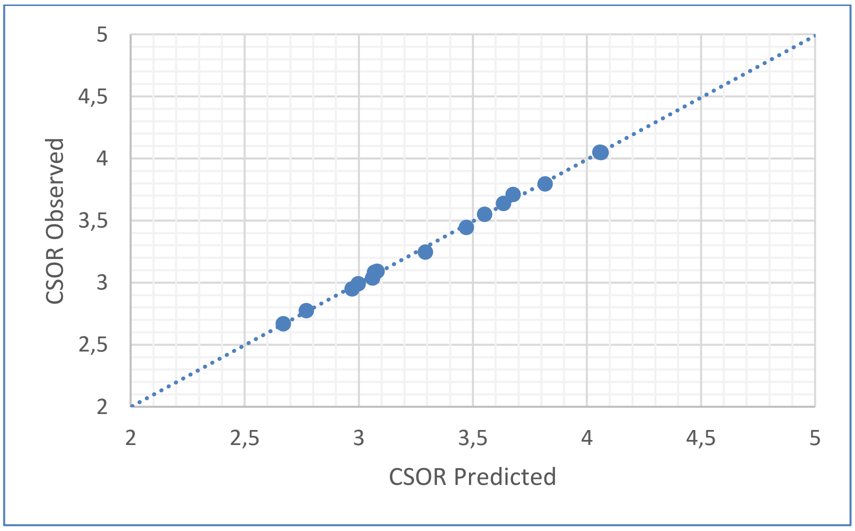
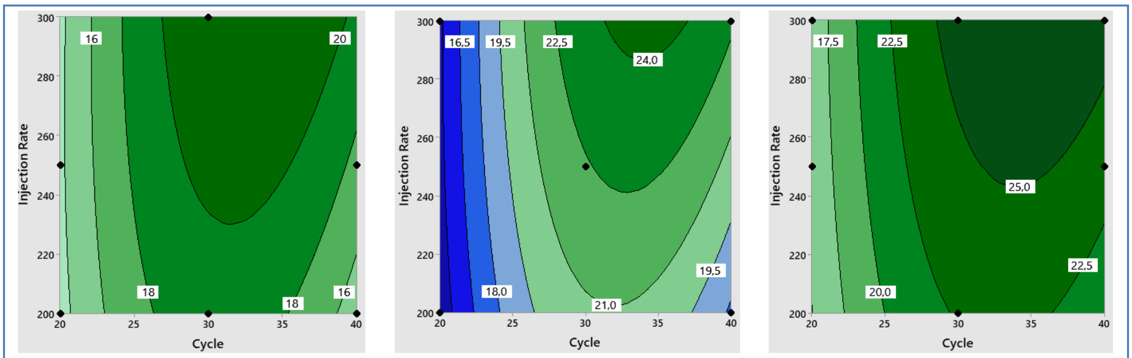


Figure 6. The relationship between CSOR observed and predicted

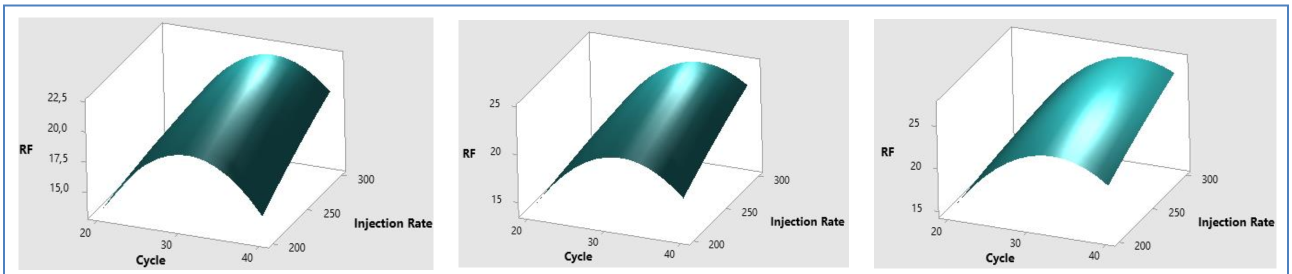
3.5. Response Optimum Condition

After analyzing the model, it means getting the conclusion that the model is suitable for estimating the optimum response. Furthermore, the optimization stage is carried out. The first optimization is done to find the maximum RF without paying attention to the CSOR, while the second optimization looks for the minimum CSOR without paying attention to the RF, and the third optimization is carried out by optimizing the RF and minimizing the CSOR by observing the relationship between the two. At this phase, optimization is carried out by analyzing the contour plot, surface plot, and response optimizer. The response optimizer on Minitab 19 can predict the optimum conditions of response and provide a combination of definite values for each independent variable.



SQ = 0.5 SQ = 0.7 SQ = 0.9

Figure 7. Response contour plot for the first optimization



SQ = 0.5 SQ = 0.7 SQ = 0.9

Figure 8. Response surface plot for the first optimization

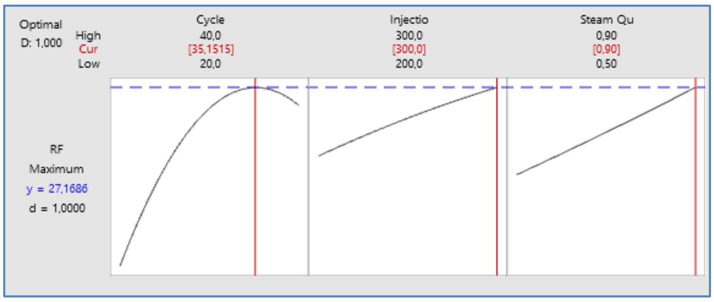


Figure 9. Response optimizer result for the first optimization

In the first optimization, based on the contour plot can be seen **Figure 7**, the optimal RF conditions are at a steam quality of 0.9, between 30 to 40 cycles, and at an injection rate of 240 to 300 bbl/day with RF> 25%. To see more clearly, the analysis will proceed to the surface plot can be seen **Figure 8**, on the surface plot the optimal conditions are at a steam quality of 0.9, between 30 to 40 cycles, and at an injection rate of 300 bbl/day with predictions above 25%. The optimal conditions for obtaining RF are based on the response optimizer on Minitab 19 can be seen **Figure 9**, the cycle price is 35 cycles, the injection rate is 300 bbl/day, the steam quality is 0.9. Where obtained an RF prediction of 27.1686% with a prediction interval from 24.907% to 29.43%.

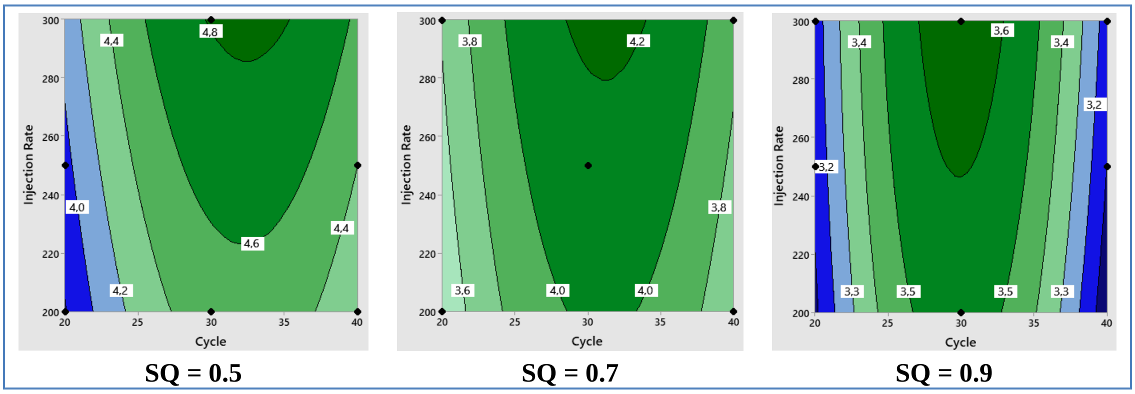


Figure 10. Response contour plot for the second optimization

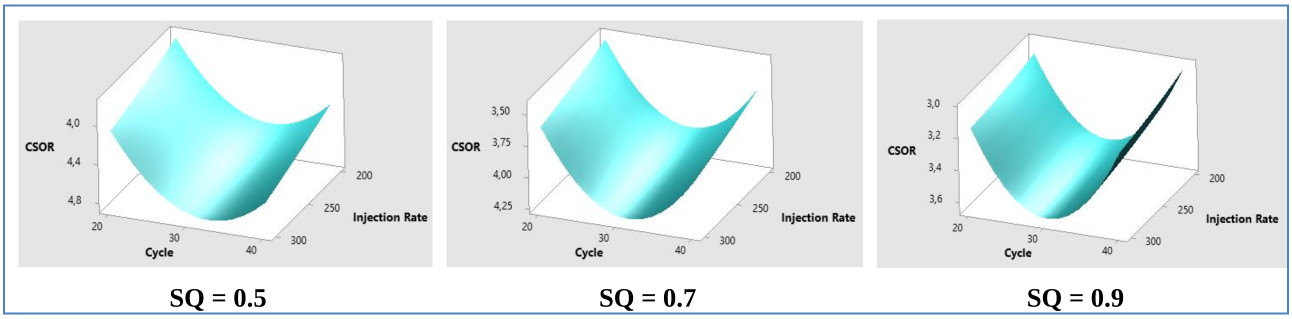


Figure 11. Response surface plot for the second optimization

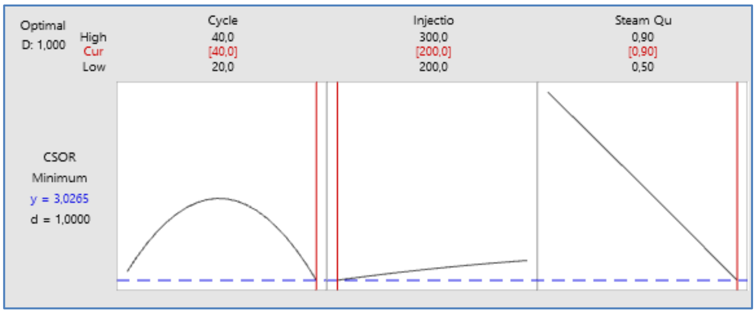


Figure 12. Response optimizer result for the second optimization

In the second optimization, based on the contour plot can be seen in **Figure 10**, the minimum condition for CSOR is at a steam quality of 0.9, with cycles of less than 22 and more than 38, and at an injection rate of between 250 to 300 bbl/day with CSOR <3, 2. On the surface plot can be seen **Figure 11**, the optimal conditions are at a steam quality of 0.9, 40 cycles, and an injection rate of 200 bbl/day with a prediction of less than 3.2. The optimal conditions for obtaining CSOR are based on the response optimizer on Minitab 19 can be seen **Figure 12**, the cycle price is 40 cycles, the injection rate is 200 bbl/day, the steam quality is 0.9. Where the CSOR prediction is obtained for 3.0265 with a prediction interval from 2.586 to 3.467.

To find the relationship between the two responses which is RF and CSOR, a third optimization was carried out to find the value by maximizing RF and minimizing CSOR by taking observing the relationship between the two responses. Based on the response optimizer from Minitab 19 (Figure 3.17), the combined cycle parameter values are 39, an injection rate of 300 bbl/day, and a steam quality of 0.9. The CSOR prediction is 3.1902 with the prediction interval from 2.8391 to 3.5412, while the RF prediction is 26.2358% with the prediction interval from 23.899% to 28.572%.

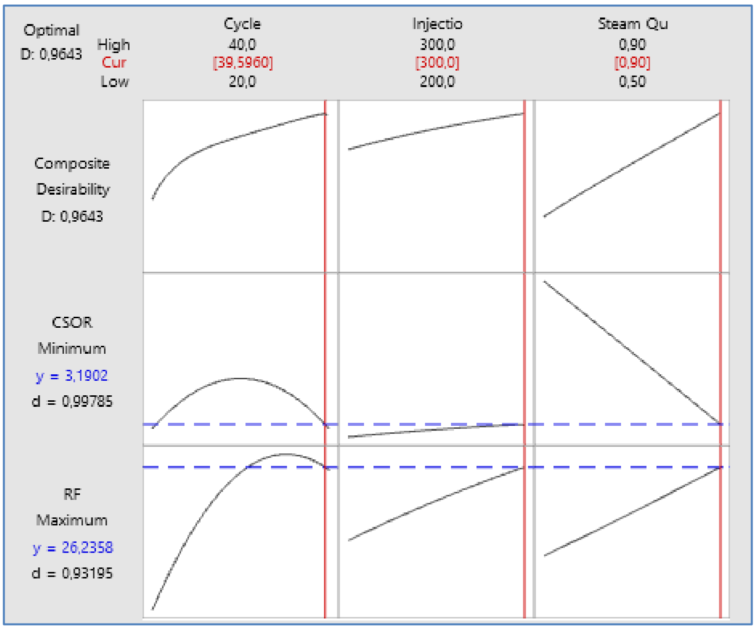


Figure 13. Response optimizer result for the third optimization

3.6. Verification Test

To confirm the predictions of the optimum conditions of cycle, injection rate, and steam quality, verification is done. Based on the predicted value of the Response Surface Method for the first optimization, verify a scenario with 35 cycles, an injection rate of 300 bbl/day, and a steam quality of 0.9 to obtain the maximum RF value. For the second optimization, verify a scenario with 40 cycles, an injection rate of 200 bbl/day, and a steam quality of 0.9 to obtain a minimum CSOR. In the third optimization, verify a scenario with a 39 cycles scenario, an injection rate of 300 bbl/day, and a steam quality of 0.9.

Table 7. Verification result for the first optimization scenario

Cycle (times)	Injection Rate (bbl/day)	Steam Quality	RF (%)	
			Predicted	Observed
35	300	0,9	27,1686	25,0513

Table 8. Verification result for the second optimization scenario

Cycle (times)	Injection Rate (bbl/day)	Steam Quality	CSOR	
			Predicted	Observed
40	200	0,9	3,0265	3,2157

Table 9. Verification result for the third optimization scenario

Cycle (times)	Injection Rate (bbl/day)	Steam Quality	RF (%)		CSOR	
			Predicted	Observed	Predicted	Observed
39	300	0,9	26,2358	24,1020	3,1902	3,5129

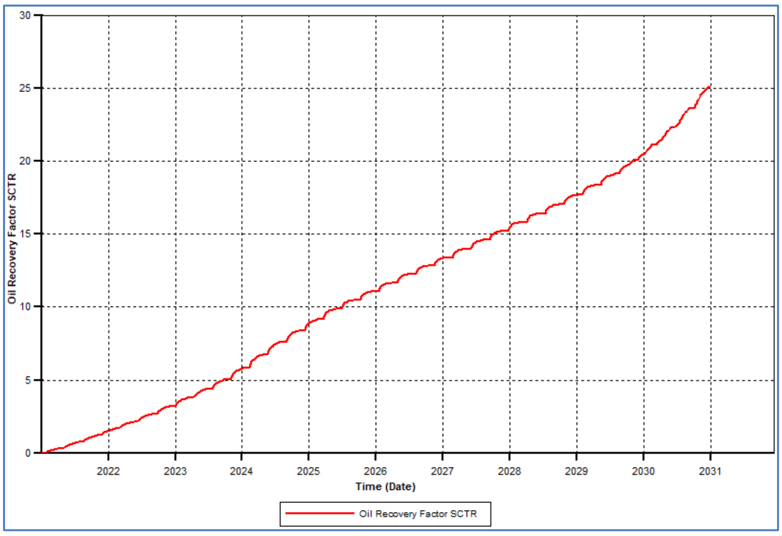


Figure 14. RF result for the first optimization scenario

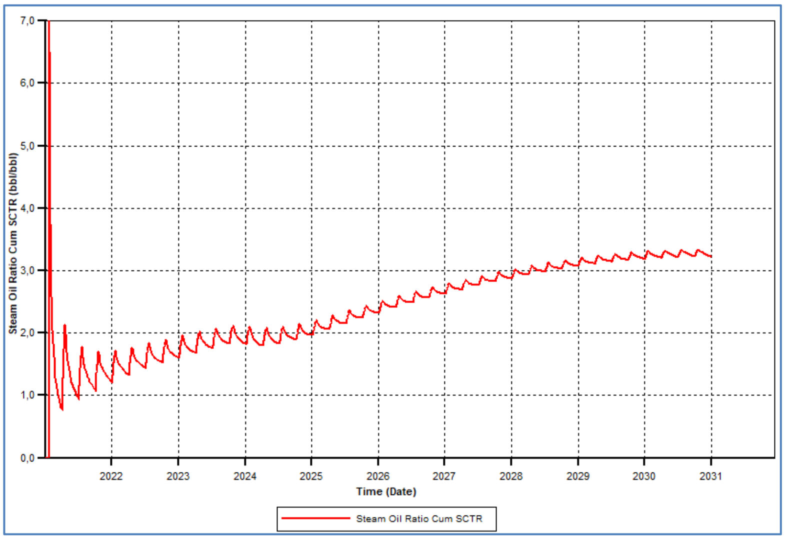


Figure 15. CSOR result for the second optimization scenario

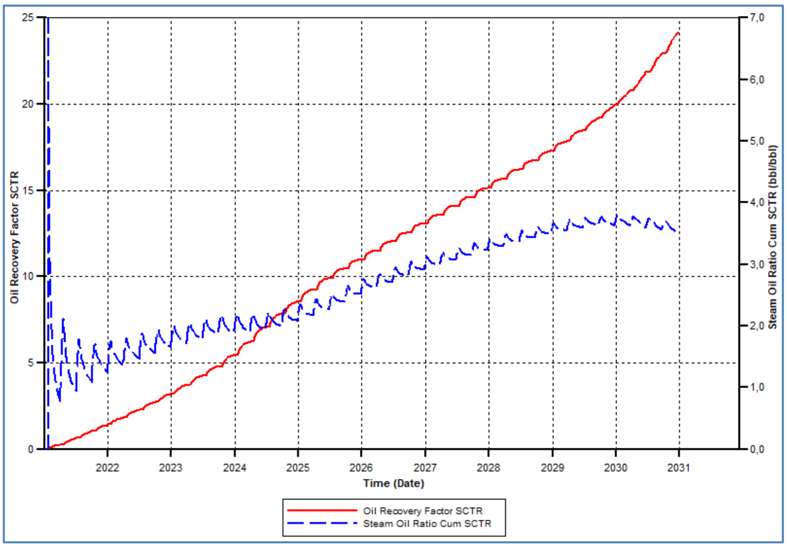


Figure 16. RF and CSOR result for the third optimization scenario

In the verification of the first optimization model, the RF results obtained were 25.0513% can be seen in **Figure 14** with an accuracy level of 92.207%. In this scenario, the CSOR is 3.48352.

In the verification of the second optimization model, the CSOR value is 3.21572 can be seen in **Figure 15** with an accuracy level of 94.116%. In this scenario, the RF value is 19.7284%.

In the verification of the third optimization model, the RF values obtained were 24.102% and CSOR 3.5129 with an accuracy level for RF of 91.867% and CSOR of 90.814%. The relatively high accuracy value indicates that the model used in the study is valid.

IV. CONCLUSION

This research demonstrates that the cyclic steam stimulation process can be optimized by using response surface methodology. There are three parameters that can be optimized such as CSS cycle, steam injection rate, and steam quality.In the ANOVA table, the P-value at cycle, injection rate, and steam quality are less than the significant level. Whereas in the Model Summary Table, the value of S is small and R-sq is classified as large and in the Residual Plot, almost all of the graphs are normally distributed. So it can be concluded that the parameters have a statistically significant effect on the response and this model is good at describing the response at the optimization phase. Based on the simulation results, shows that the CSS cycle, steam injection rate, and steam quality affect the RF and CSOR. The maximum RF results with the minimum CSOR were obtained at 39 cycles, an injection rate of 300 bbl/day, and a steam quality of 0.9 with an RF and CSOR value is 24.102% and 3.5129 respectively. Therefore, it can be concluded that CSS will bring significant advantages to heavy oil production.

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