Analysis of Factors Affecting Polymer Flooding Based on a Response Surface Method

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ABSTRACT: Both polymer injection time and injection rate play an important role in the development of an offshore reservoir with a limited service life of the platform. To quantitatively and qualitatively investigate the influence of the formation packing sequence, injection rate, polymer injection timing, and their interaction on the performance of polymer flooding, a numerical reservoir model is simulated in this study based on the properties of offshore reservoir LD in China. Also, the polymer flooding experimental scheme is designed according to the response surface method and single-factor analysis method. Based on numerical simulation and statistical analysis, a regression model is established to predict the incremental oil recovery factor of polymer flooding. The analysis of variance (ANOVA) shows that the regression model fits well with the experimental data. The three factors’ influence capacities on the increased oil recovery factor from large to small are the injection rate, formation rhythm, and injection timing. From the analysis, it is also found that the improved polymer flooding performance can be achieved under an injection rate of 0.07–0.09 PV/a and an injection timing of 30% water cut for positive rhythm formation.

1. INTRODUCTION
Polymer flooding has been widely applied to improve the areal and vertical sweep efficiency of the reservoir after waterflood.1−4 It has become an important method for enhancing oil recovery in the offshore reservoir. The short service life of the platform and demand for high oil production rates make the research on polymer injection timing a priority over other injection parameters.5 Meanwhile, the optimization of injection parameters for polymer flooding is a multifactor and multilevel composite system in which different factors interfere with each other making the study complicated.

Many scholars used single-factor analysis,6,7 uniform design,8 and orthogonal design methods9,15 to investigate the influencing factors during polymer flooding and optimize polymer injection parameters. The response surface method (RSM) uses a second-order mathematical model between the response output and influencing factors as an approximation of the true functional relationship based on statistical analysis.10,11 The RSM has been widely used in research fields such as electronics, machinery, agriculture, the chemical industry, and industrial process improvement12 and has also been used in the petroleum industry research field in recent years.13−16 The Box–Behnken design (BBD) and central composite design (CCD) are the most common designs of the response surface methodology and have been widely used in various experiments.17 The BBD is based on three-level incomplete factorial designs18,19 and has been applied in optimization processes due to its reasoning design and excellent outcomes. Symmetrical experimental designs (three-level factorial, BBD, CCD, and Doehlert designs) are compared in terms of characteristics and efficiency in Bezerra et al.’s work.20 An early systematic work was done by Zhang et al.21 where they performed 158 simulations based on the CCD to generate the response model for surfactant/polymer flooding optimization. Al-Mudhafar et al.22,23 used a proxy-based meta-modeling optimization method in the CO2-GAGD modeling process; constructing a proxy model by up to 176 and 256 runs to find the optimal level for each operational factor, many design of experiment (DOE) approaches have been used in various reservoir simulation studies to build the proxy models: fractional factorial design,24 central composite design,25 D-optimal design,26 and Latin hypercube design.27

However, there are few studies on quantitative analysis of factors influencing polymer flooding in the offshore reservoir.
with a limited platform lifetime. Meanwhile, few methods require a large number of simulation runs, which spend lots of time. For this reason, response surface methodology combined with single-factor analysis was adopted for the experimental design and statistical analysis of the experimental results to illustrate the influencing manner of formation rhythm, injection rate, polymer injection timing, and their interaction effects on polymer flooding performance.

2. GEOLOGICAL MODEL AND DESIGN OF EXPERIMENT

2.1. Model Setup. Taking an L block in the Bohai reservoir as a prototype, ECLIPSE numerical simulation software was used to build a conceptual model for the reservoir, and a five-spot well pattern was adopted for numerical simulation. In directions of I, J, and K, the reservoir is divided into a grid system of 30 × 30 × 10, and the size of each grid in the model is 10 m × 10 m × 1 m. The thickness of the oil layer is 10 m, and the porosity is 33%. The average permeability of the homogeneous model, positive rhythm model, and negative rhythm model is 2000 mD. The density of the crude oil is 0.87 g/cm³ with a viscosity of 20 mPa·s. Moreover, the oil formation volume factor is 1.12, and the oil compressibility coefficient is 2.5 × 10⁻⁴ MPa⁻¹. In addition, the density of formation water is 1.03 g/cm³ with a viscosity of 0.92 mPa·s. The water formation volume factor is 1.01, and the compressibility coefficient is 5 × 10⁻⁴ MPa⁻¹. Meanwhile, the initial formation pressure is around 11.2 MPa.

2.2. Experimental Scheme and Results. According to the BBD and response surface method, the experimental scheme was designed using Design-Expert software. The incremental oil recovery of polymer flooding was taken as the response variable along with three influencing factors of formation rhythm, injection rate, and injection timing. Each factor was taken at three levels, and a response surface method analysis was conducted. The Box–Behnken design method including influencing factor levels and response variables is shown in Table 1. The experimental scheme and results are shown in Table 2.

| Table 1. Levels and Values of Box–Behnken Design Factors and the Response Variable |
|---------------------------------|---------------|---------------|-------------------|
| formation heterogeneity | injection rate (PV/a) | water cut when polymer was injected | increased oil recovery factor |
| −1 positive rhythm | 0.03 | 30% | 1.01 |
| 0 homogeneous | 0.07 | 60% | 1.05 |
| 1 negative rhythm | 0.11 | 90% | 1.09 |

“Positive rhythm: permeability is greater at the bottom (downward coarsening); negative rhythm: permeability is lower at the bottom (upward coarsening).”

3. RESULTS AND DISCUSSION

3.1. Multiple Linear Regression Model. The polymer flooding numerical experimental was conducted according to the Box–Behnken design method, and the increased oil recovery factor of each case was obtained. Using Design-Expert software, the coefficients of the regression model, formation rhythm, injection rate, and polymer injection timing were calculated by multiple regression analysis. The mathematical regression model is

\[ \Delta R = 24.73 - 2.27 \times A + 8.21 \times B + 1.29 \times C - 1.25 \times AB + 2.89 \times AC + 0.19 \times BC - 0.4375 \times A^2 - 4.52 \times B^2 - 2.05 \times C^2 \]

In the formula, \( \Delta R \) is the incremental oil recovery factor (%), \( A \) is the formation heterogeneity, the values are −1, 0, and 1 when the formation is positive, homogeneous, and negative, respectively, \( B \) is the injection rate (PV/a), and \( C \) is water cut when the polymer is injected.

Figure 1 shows the comparison of simulation results and values that are predicted by the regression model. It can be seen that the proposed regression model fits well with the results from the numerical simulation. Moreover, the variance

Table 2. Simulation Schedule and Result for the Box–Behnken Design

| case | formation heterogeneity | injection rate (PV/a) | injection time | increased oil recovery factor |
|------|------------------------|-----------------------|---------------|-----------------------------|
| 1    | homogeneous            | 0.03                  | 90%           | 9.57                        |
| 2    | homogeneous            | 0.07                  | 60%           | 24.73                       |
| 3    | negative rhythm        | 0.03                  | 60%           | 12.35                       |
| 4    | negative rhythm        | 0.07                  | 60%           | 24.73                       |
| 5    | positive rhythm        | 0.07                  | 90%           | 26.19                       |
| 6    | positive rhythm        | 0.11                  | 60%           | 29.69                       |
| 7    | negative rhythm        | 0.07                  | 90%           | 23.83                       |
| 8    | homogeneous            | 0.07                  | 60%           | 24.73                       |
| 9    | negative rhythm        | 0.11                  | 60%           | 26.25                       |
| 10   | homogeneous            | 0.07                  | 60%           | 24.73                       |
| 11   | homogeneous            | 0.07                  | 60%           | 24.73                       |
| 12   | homogeneous            | 0.11                  | 30%           | 26.38                       |
| 13   | negative rhythm        | 0.03                  | 30%           | 12.52                       |
| 14   | positive rhythm        | 0.03                  | 60%           | 10.81                       |
| 15   | homogeneous            | 0.03                  | 30%           | 10.32                       |
| 16   | homogeneous            | 0.11                  | 90%           | 26.39                       |
| 17   | positive rhythm        | 0.07                  | 30%           | 26.44                       |

Table 3. Single-Factor Analysis

| formation heterogeneity | injection rate (PV/a) | injection time | recovery factor increased (%) |
|------------------------|-----------------------|---------------|-------------------------------|
| positive rhythm        | 0.07                  | 30%           | 26.1                          |
| homogeneous            | 0.07                  | 30%           | 23.98                         |
| negative rhythm        | 0.05                  | 22.19         | 24.78                         |
| positive rhythm        | 0.07                  | 30%           | 26.44                         |
|                      | 0.09                 | 28.5          | 24.78                         |
|                      | 0.11                 | 29.68         | 26.44                         |
| positive rhythm        | 0.07                  | 60%           | 26.41                         |
|                      | 0.07                 | 75%           | 26.35                         |
|                      | 0.07                 | 90%           | 26.19                         |

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As shown in the results, the influencing factors A and B are found to be significant. Also, the P value indicates that the interaction factors BC, A\(^2\), and AB are not significant. The absolute value of the coefficient estimated by each factor shows that the degree of influence of each factor on the response is \(B > B^2 > A > AC > C > AB\), where factors B, C, and AC have positive effects, while A, AB, and B\(^2\) have negative effects.

### 3.2. Influencing Factor Analysis of Polymer Flooding

#### 3.2.1. Formation Heterogeneity

It can be seen from the contour map of the increased oil recovery factor that, under different formation rhythm conditions (Figure 2), there is no obvious change in the contour distribution density of the increased oil recovery factor value, indicating a lesser influence of formation rhythm on the interaction of the polymer injection rate and injection time. The injection rate has a similar effect on polymer flooding under a different model, as shown in Figure 2a. The increased oil recovery factor increases with the injection rate while keeping injection timing constant. Meanwhile, under the constant injection rate, the influence of factors on polymer flooding under different formation rhythm varies with the injection timing. For positive rhythm formations, a better performance will be obtained through early polymer injection. For the homogeneous model, the injection timing has less effect. Meanwhile, in the negative rhythm model, with the increased polymer injection time, the recovery factor of polymer flooding decreases instead. As the highest permeability is at the top of the negative rhythm reservoir, the polymer injected into formation in an earlier stage will preferentially enter into the top layer. This high viscosity characteristic will make it difficult for gravity segregation to take effect, which will lead to poor sweep efficiency.

Figure 3 shows the recovery factor and increased oil recovery factor of water and polymer flooding under different formation heterogeneity. It can be seen that the water flooding performance in positive rhythm formation was poorer than those in homogeneous and negative rhythm formation. This is mainly due to the combined effects of gravity segregation and water channeling, which lead to an early water breakthrough in formation with a high permeability layer distributed on the bottom. Meanwhile, for water flooding in negative rhythm formation, the gravity segregation effects tend to divert more water within the top high permeability layer into the bottom low permeability layer, thus leading to a more even displacement front. After polymer flooding, the flooding performance was improved in all formations, and the increased oil recovery was significant in positive rhythm formation, which indicates potential for initiating polymer flooding.

#### Table 4. ANOVA of the Multiple Linear Regression Model

| sources of variation | sum of squares | degree of freedom | mean square | F value | P value |
|----------------------|----------------|-------------------|-------------|---------|---------|
| regression model     | 743.99         | 9                 | 82.67       | 13.38   | 0.0012  |
| lack of fit          | 23.25          | 3                 | 7.75        |         |         |
| pure error           | 20             | 4                 | 5           |         |         |
| sum                  | 787.24         | 16                |             |         |         |

Figure 1. Comparison of simulation results and the calculated value by the regression model.

As shown in the results, the regression model fits the experimental data well. The complex correlation coefficient r is determined to be 0.95. The complex correlation coefficient is an indicator to test the regression effect. A value closer to 1 represents a good regression fit. In this study, the correction decision coefficient is 0.87, which is relatively closer to 1, representing a good correlation between the actual value and the prediction. The above analysis has shown that the mathematical regression model has a good fitting with the experimental data, including a smaller error. This model can be used to analyze and predict the increased oil recovery factor of polymer flooding.

The P value represents the significance level of the model and each influencing factor. The value of P less than 0.05 (P < 0.05) indicates that the model and each factor have a significant influence on the response. The estimated coefficients of the regression model are presented in Table 5.

#### Table 5. Estimated Coefficients of the Mathematical Regression Model

| influencing factor | estimated coefficient | degree of freedom | standard deviation | confidence lower limit | confidence upper limit | P value |
|--------------------|-----------------------|-------------------|--------------------|------------------------|------------------------|---------|
| constant           | 24.73                 | 1                 | 1.11               | 22.1                   | 27.36                  | 0.0012  |
| A\(^{-2}\)          | -2.27                 | 1                 | 0.8789             | -4.35                  | -0.1943                | 0.0362  |
| B\(^{-2}\)          | 8.21                  | 1                 | 0.8789             | 6.13                   | 10.29                  | <0.0001 |
| C\(^{-2}\)          | 1.29                  | 1                 | 0.8789             | -0.7882                | 3.37                   | 0.1856  |
| AB                 | -1.25                 | 1                 | 1.24               | -4.18                  | 1.69                   | 0.3499  |
| AC                 | 2.89                  | 1                 | 1.24               | -0.049                 | 5.83                   | 0.0530  |
| BC                 | 0.19                  | 1                 | 1.24               | -2.75                  | 3.13                   | 0.8828  |
| A\(^2\)            | -0.4375               | 1                 | 1.21               | -3.3                   | 2.43                   | 0.7286  |
| B\(^2\)            | -4.52                 | 1                 | 1.21               | -7.38                  | -1.65                  | 0.0074  |
3.2.2. Injection Rate. Figure 4 represents a contour map of the increased oil recovery factor under different injection rates. It can be seen that, with the increase of the injection rate, the contour distribution of the increased oil recovery factor becomes denser, indicating that the injection rate has a greater influence on the interaction between formation rhythm and injection timing. As the injection rate increases, polymer flooding that increased the oil recovery factor increases.

The single-factor analysis result of the impact of the injection rate on the oil displacement effect in the positive rhythm formation is shown in Figure 5. The result reveals that, with the increase of the injection rate, the incremental oil recovery factor of polymer flooding gradually increases. When the injection rate is greater than 0.09 PV/a, the increasing tendency becomes slower. The increase in the injection rate or displacement pressure difference effectively alleviates the rapid flow of water in the bottom high permeability layer due to the oil-water gravity segregation and also increases the sweep efficiency of the top low permeability layer. However, there is an optimal injection rate between 0.07 and 0.09 PV/a. After exceeding the optimal injection rate, it has limited enhancement on the increased oil recovery factor.

3.2.3. Polymer Injection Timing. The contour map of the increased oil recovery factor under different injection timing (Figure 6a) shows that the increase of water cut when a
polymer is injected results in a little change in the distribution of contour, as compared with those in Figure 6b,c. This indicates that the polymer injection timing has a small influence on the interaction between formation rhythm and the injection rate. Moreover, the increased oil recovery factor increases with the injection rate. Meanwhile, it can be seen that the injection timing has different feasibility under different formations. For positive rhythm formation, the earlier the injection timing, the greater the increased oil recovery factor. For the negative rhythm formation, a better increased oil recovery factor can be obtained when the polymer is injected at 90% water cut.

Figure 7 presents the single-factor analysis of the impact of the injection timing on the oil displacement. In positive rhythm formations, it can be seen that, with the increase in water cut, the incremental recovery factor of polymer flooding decreases gradually. When the polymer injected at water cut is greater than 60%, the increased oil recovery factor is reduced significantly. Therefore, polymer flooding should be initiated at a low water cut for offshore oil fields.

4. CONCLUSIONS
Combining response surface analysis and single-factor analysis, several numerical schemes were designed and simulated, and the influences of the formation rhythm, injection rate, and polymer injection timing, and their interaction on the performance of polymer flooding were quantitatively and qualitatively investigated based on the simulation results; the following conclusions were drawn:

(1) A mathematical regression model considering different geological and operation parameters can be generated through multiple regression analysis of the simulation results. Based on this model, it is possible to analyze and predict the polymer flooding performance under different parameter combinations.

(2) The extent of the impact on the polymer flooding performance from large to small is the injection rate, formation rhythm, and injection timing. For positive rhythm and homogeneous formation, early polymer injection would get better polymer flooding performance; however, a delayed polymer injection is more feasible for negative rhythm formation.

(3) The positive rhythm formation obtains a larger increased oil recovery factor of polymer flooding than the homogeneous and negative rhythm formation. As the injection rate increases or the timing of polymer injection advances, the increased oil recovery factor of polymer flooding increases. For the offshore reservoir of the L block, the optimal increased oil recovery factor will be obtained under an injection rate of 0.07−0.09 PV/a and the polymer injected at 30% water cut.

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Notes
The authors declare no competing financial interest.

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