A Novel Workflow to Design and Optimize the Parameters of Polymer Flooding Based on OED-PCA-RA Method

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Abstract: In this study, a decision-making workflow to design and optimize parameters of polymer flooding is put forward. This technological process is divided into three phases. The first phase is to design five-parameter and five-level orthogonal experiments (OED). The second is to systematically evaluate experiment results by mathematical method principal component analysis (PCA) based on ten subfactors from three aspects, including injection effect, development effect and economic benefits. The third is to analyze sensitivity by range analysis (RA) based on the comprehensive evaluation result and then obtain optimized parameters. Finally, the parameter optimization in Xinjiang reservoir is performed through this workflow.

1. Introduction

Polymer flooding technology is an effective method to improve oil recovery in water-flooding oilfield, and its role in oilfield development is paid more and more attention (A. Kumar Sinha et al., 2015). In the design of the polymer flooding scheme, it is necessary to select a polymer scheme suitable for the reservoir conditions (Jianian Xu, et al., 2018). Badar Al-Shakry et al. (2018) optimized the injection by analyzing the injectivity of polymer solution. Ali Bengar et al. (2017) empolyed ANOVA and tornado charts to study the important parameters of polymer flooding after determining the main effects and interaction, and then chose three factors in oil production. However, these methods are either unable to analyze the correlation between parameters, or the number of experimental samples is too large to analyze one by one. In the evaluation of the effect of polymer flooding, traditional methods are mainly focused on oil production or economy viability only because the two objectives can be conflicting and not easy to balance. Peerapong Ekkawong et. (2017) utilized the concept of Pareto optimality to generate a set of Pareto optimal solutions. Yanbin Wang. (2014) proposed an approach for evaluation of polymer flooding potential during oil reservoir development, which integrated orthogonal design and BP artificial network. These methods can only consider few evaluation indexes and are not able to achieve comprehensive evaluation on the development effect of polymer flooding. In this study, the orthogonal experiment is designed to synchronously analyze the effect of every injection parameter. In the aspect of development performance, we choose principal component analysis (PCA), which enable to assess more indexes and avoid the risk of expert decision. In addition, the range analysis is employed to quantify the sensitivity of parameters and get the optimal combination of injection parameters. The entire approach aims to minimize the risk of manual decision making to some extent and obtain the best decision-making plan.

2. OED-PCA-RA METHOD

A complex and systematic structure of the method is represented by a diagram in Figure 1. And the method is briefly described.

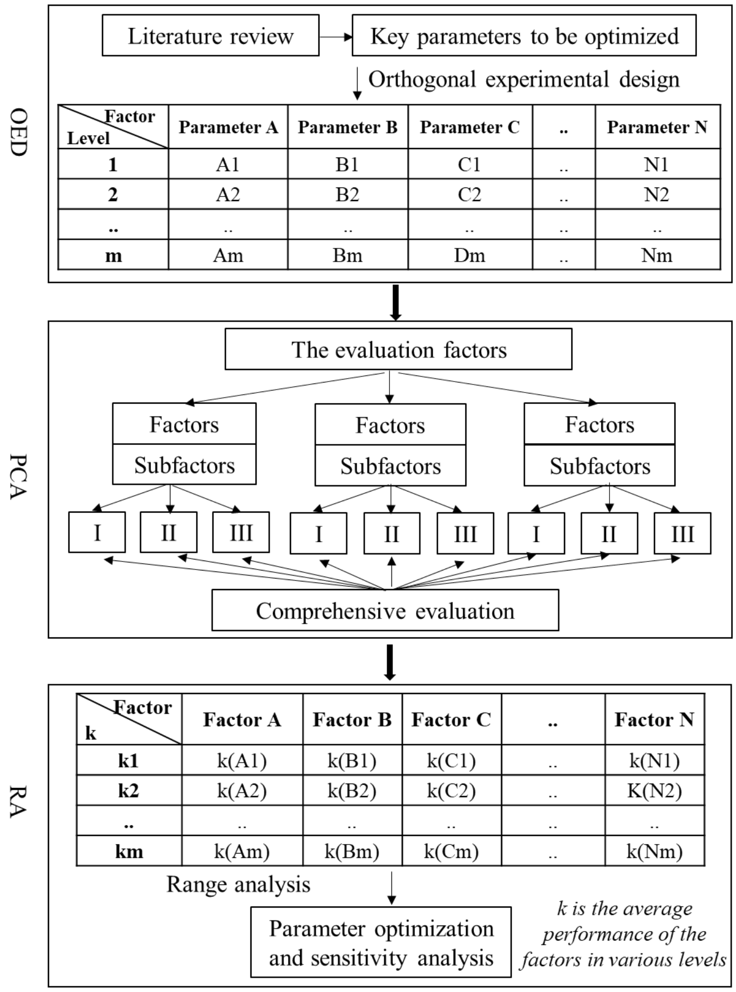


Figure 1: Generalized framework for parameters optimization and comprehensive assessment through the approach using OED-PCA-RA analysis.

OED Method: The OED is a method mainly to study the experimental design with multiple factors and levels, which was put forward by the famous Japanese statistician Genichi Taguchi. The method is to select some representative points to carry out the test from the comprehensive test based on orthogonality, these representative points have the characteristics of "uniform dispersion, homogeneous and comparable". OED is not only the main method of fractional factorial design but also an efficient, rapid and economical experimental design method (Yanbin Wang et al. 2014).

Taking the three-factor and three-level experiment as an example, in order to conduct a comprehensive experiment, it is necessary to design 3×3×3=27 groups of experiments. While only 9 groups of experiments need to be designed if considering orthogonal experiment, which not only greatly reduces the workload, but also analyzes the influence of all factors on the test results.

PCA: Principal component analysis (PCA) is a mathematical dimensionality reduction method, which is designed to calculate the overall effects by finding a way to recombine the original numerous variables with certain correlation into a new set of independent comprehensive variables (Put forward by Karl Pearson). In general, the Mathematical treatment is to make linear combinations of the original variables as the new synthesis variables. However, if such combinations are not restricted, there may be a large number of combinations, which make it difficult to choose. If label the first linear combination (also known as the first synthetic variable) we pick as F1, we naturally want it to reflect as much information as possible about the original variable. Here, "information" is measured by variance. That is, the Var (F1) should be as large as possible, and contains more information. Therefore, F1 should have the largest variance among all linear combinations, so F1 is called the first principal component. If the first principal component is insufficient to represent the information of p variables, then F2, the second linear combination, is selected. In order to effectively reflect the original information, the existing information of F1 does not need to appear in F2, which is expressed in mathematical language to require cov (F1, F2) =0 and called F2 as the second principal component. In the same way, the third, fourth... p principal components are obtained. Note: cov represents covariance in statistics. Last the new data of each factor under each principal component, namely the score of principal components, can be obtained according to the original standardized data and the main component expressions of each sample (Hyungsik Jung et al. 2018).

RA: The range analysis, also known as the R method, includes two steps of calculation and judgment. In the process of range analysis, K(Nm) is the total mark of parameter N at m level, and k(Nm) is the average value of K(Nm). The optimal level of parameters and the optimal combination of all parameters can be judged by the size of k value. The size of R(N) reflects the variation of the test mark when the parameter N takes different values. The larger the value is, the greater the influence of the parameter on the test mark is. Therefore, the less it can be ignored of higher R in the subsequent experimental design because of its greater sensitivity (Zikang Xiao et al. 2019).

3. Polymer Injection Decision-Making Work Flow

3.1.The OED Process

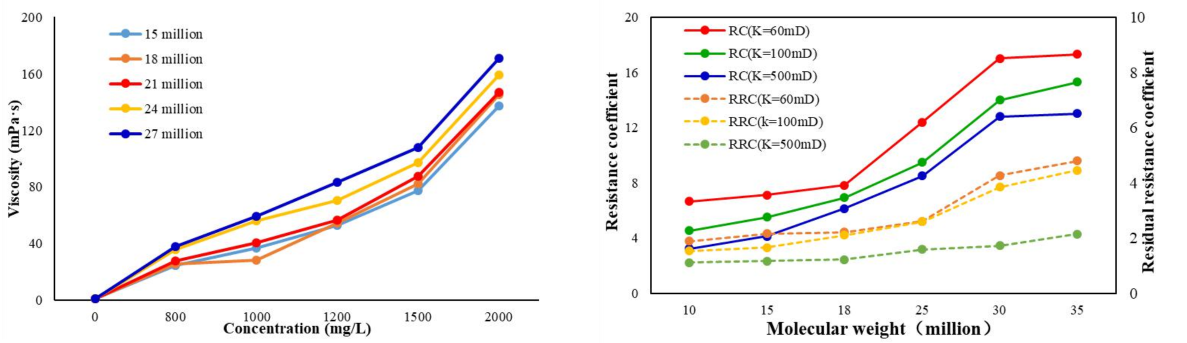
There are five main injection parameters for polymer solution: polymer solution concentration, polymer injection volume, injection speed, injection timing and polymer molecular weight respectively (Qing You et al., 2019). They are denoted as five parameters in the orthogonal test. For each parameter, different values can be set, denoted as level values. In order to ensure the accuracy and comprehensiveness of the results, we set five levels, which are recorded as five-factor, five-level orthogonal experiment. To quantify the value of parameters and then pick the level, we select a well group in Xinjiang oilfield. The basic data of this well group are shown in Table 1.

Table 1: Basic data of the well group.

Objects	Values	Unites
The depth of oil reservoir	1150	m
Temperature of oil reservoir	39	℃
Reservoir water salinity	28860	mg/L
Rock compressibility	0.0003	1/Bars
Average porosity	0.13	dimensionless
Average permeability	155	mD
Oil viscosity	34	cp
Variation coefficient of K	0.48	dimensionless
Well pattern	Five-point	dimensionless
Current water cut	61%	dimensionless

It is a conglomerate reservoir with strong stratigraphic heterogeneity and undeveloped fractures. At present, the oilfield has entered the stage of high water cut development, with low water flooding recovery rate, so it is urgent to carry out polymer flooding test.

When the ratio of polymer molecular size to pore throat radius of reservoir rock is above five, the polymer and rock pore have a good match (Gu Hongjun et al. 2016). For this reason, the molecular weight range of polymers we picked is set at 15m-27m. And some relevant parameters on polymer solution are obtained through laboratory experiments, as shown in Figure 2, which are essential parameters for subsequent numerical simulation.



(a) (b)

Figure 2: a. Viscosity - concentration curves of polymer solution under different molecular weight; b. The relationship of core resistance coefficient (RC) and residual resistance coefficient (RRC) with molecular weight of polymer under different rock permeability.

Based on the theory of OED, five factors and five levels of orthogonal experiment are designed, the specific information is listed in the Table 2.

Table 2: The final design results based on the principle of orthogonal test.

Plan	A (mg/L)	B (PV)	C (PV/a)	D (fw)	E (million)
1	1000	0.2	0.12	0.65	15
2	1000	0.4	0.15	0.72	18
3	1000	0.6	0.18	0.79	21
4	1000	0.8	0.21	0.86	24
5	1000	1	0.24	0.9	27
6	1200	0.2	0.15	0.79	24
7	1200	0.4	0.18	0.86	27
8	1200	0.6	0.21	0.9	15
9	1200	0.8	0.24	0.65	18
10	1200	1	0.12	0.72	21
11	1400	0.2	0.18	0.9	18
12	1400	0.4	0.21	0.65	21
13	1400	0.6	0.24	0.72	24
14	1400	0.8	0.12	0.79	27
15	1400	1	0.15	0.86	15
16	1600	0.2	0.21	0.72	27
17	1600	0.4	0.24	0.79	15
18	1600	0.6	0.12	0.86	18
19	1600	0.8	0.15	0.9	21
20	1600	1	0.18	0.65	24
21	1800	0.2	0.24	0.86	21
22	1800	0.4	0.12	0.9	24
23	1800	0.6	0.15	0.65	27
24	1800	0.8	0.18	0.72	15

3.2.The PCA Process

Conventional evaluation methods often list the development effects of individual major factors (such as oil production, water cut), which usually lead to incomplete evaluation results and cannot truly and effectively reflect the development effects. Hence, we consider three aspects from injection effect, development effect and economic benefits of well group to systematically and comprehensively evaluate the overall performance.

3.2.1. The Definition of Subfactors

Each factor is further divided into corresponding subfactors. The definitions of all subfactors are in Table 3. This is vital to obtain effective information during the evaluation.

Table 3 The specific definitions of all subfactors.

Factors	Subfactors	Definition of Subfactors
Injection effect	Ratio of well group pressure rise(a)	Refers to the ratio of the difference between the maximum injection pressure and the pressure value when polymer flooding works to the maximum pressure value.
	Ratio of apparent water absorption index(b)	Refers to the ratio of apparent water absorption index before and after profile control. If the ratio is greater than 1, the reservoir water absorption capacity decreases after profile control.
Development effect	Response time of production well(c)	Refers to the time interval that the water cut of a well group begins to decrease after polymer flooding.
	Effective period(d)	Refers to the period from the time that water cut starts to decline to the time that return to the original level.
	Decrease in water cut(e)	Refers to the ratio of the difference between the effective water cut (when polymer flooding works) and the lowest water cut to the effective water cut.
	Oil increment by polymer(f)	Refers to the ratio of cumulative increase in oil and polymer agent weight after regulating and flooding, which is a direct indicator of polymer flooding. The larger the value, the better the polymer flooding effect.
	Dimensionless oil increment(g)	It is the one of the most direct parameters to characterize the effect of polymer flooding. It indicates the ratio of the cumulative oil increase to the accumulated oil production during the effective period.
	EOR value(h)	Refers to the difference between the polymer flooding recovery and the water flooding recovery produced under the same injection rate. It directly indicates the increase of recovery by polymer flooding.
Economic effect	Investment payback period(i)	Refers to the time required for the total revenue from the polymer flooding to reach the total investment.
	Net present value(j)	The difference between the present value of future capital inflows (income) and outflows (expenses). In the evaluation of the polymer flooding, the cumulative net present value is a key indicator, which directly determines the economic benefits of the development plan.

3.2.2. The Evaluation Process of PCA

All the plans are numerically simulated for 15 years. Table 4 shows the result of the whole subfactors.

Table 4: Detailed numerical simulation results of all the plans. The unit of Sub(a), Sub(b), Sub(c), Sub(f), Sub(g), Sub(h) is dimensionless, the unit of Sub(c), Sub(d) is the month, the unit of Sub(i) is the year and the unit of Sub(j) is the million.

Plans	Sub(a)	Sub(b)	Sub(c) (mon)	Sub(d) (mon)	Sub(e) (%)	Sub(f)	Sub(g)	Sub(h) (%)	Sub(i) (a)	Sub(j) (mil)
1	1.29	1.59	6.00	18.00	3.63	87.55	60.30	2.35	1.67	15.75
2	1.35	1.68	4.50	35.00	8.70	62.85	70.96	6.56	2.50	22.19
3	1.39	1.79	3.00	42.00	12.95	51.09	78.18	9.87	1.71	28.63
4	1.41	1.83	1.80	55.00	16.46	44.57	84.14	9.97	2.53	30.59
5	1.42	1.84	2.00	49.00	14.27	36.82	80.99	8.14	3.83	30.93
6	1.32	1.64	3.00	39.00	13.31	115.21	72.68	5.67	1.88	20.97
7	1.35	1.71	2.80	52.00	15.61	90.84	75.98	8.58	2.30	28.98
8	1.42	1.85	2.00	50.00	13.93	47.08	81.53	7.86	3.04	24.36
9	1.46	1.92	3.50	30.00	13.68	35.28	70.93	8.07	1.88	28.11
10	1.36	1.72	5.30	52.00	13.61	41.84	71.17	12.57	3.96	35.66
11	1.44	1.92	2.50	26.00	11.08	78.80	73.02	8.62	2.29	18.11
12	1.48	1.96	2.00	28.00	7.89	76.07	78.42	7.78	1.46	27.18
13	1.49	2.00	1.50	31.00	16.19	62.76	73.37	9.81	1.67	33.24
14	1.41	1.82	4.00	67.00	18.36	58.88	78.79	11.11	3.75	39.88
15	1.42	1.85	2.50	70.00	18.51	42.00	80.16	12.63	4.58	35.81
16	1.49	1.98	1.70	31.00	16.65	123.98	72.97	7.25	1.04	24.51
17	1.49	1.99	1.50	35.00	18.58	71.74	72.89	8.22	1.88	28.19
18	1.48	1.96	2.50	70.00	22.37	68.60	77.44	11.02	4.08	33.71
19	1.49	1.98	2.50	63.00	22.07	50.11	84.13	11.83	4.58	34.77
20	1.49	1.99	2.50	45.00	16.03	49.29	78.57	15.70	2.29	40.69
21	1.50	2.01	1.50	53.00	16.58	97.50	70.15	4.87	3.33	21.40
22	1.44	1.89	3.50	61.00	25.01	75.36	74.05	9.00	4.58	29.93
23	1.48	1.97	2.50	39.00	18.99	72.20	73.82	11.19	5.21	36.58
24	1.50	2.01	1.70	58.00	19.82	53.92	79.81	13.11	3.57	37.64
25	1.50	2.01	1.50	58.00	19.61	36.44	70.84	10.34	6.04	32.89

After obtaining all the subfactors, we then use PCA to comprehensively and systematically evaluate the development effect of polymer flooding. The comprehensive evaluation results are calculated using the following process.

(1) Standardize the raw data by Z-score method; (2) Calculate the correlation coefficient matrix *R* based on the data obtained in step 1; (3) Calculate the eigenvalues and eigenvectors of the correlation coefficient matrix *R*; (4) Calculate the contribution rate b_j and cumulative contribution rate c_p of characteristic values; (5) Calculate comprehensive score. The cumulative contribution rate of the first four eigenvalues is nearly 90%, so we select them as principal components, and construct the comprehensive evaluation model Y with the contribution rates as weight.

$$Y = 0.501y_1 + 0.210y_2 + 0.102y_3 + 0.082y_4 \tag{1}$$

3.3. The RA Process

3.3.1. The Basic Theory of RA

When considering a certain factor, the range analysis (RA) considers that the influence of other factors on the result is balanced, and it is considered that the difference in the level of the factor is caused by the factor itself. Analysis of orthogonal test results by the RA should lead to the following conclusions.

(1) The sensitivity of the experimental parameters to the results; (2) The best suitable operating conditions and suitable level for the test parameters.

3.3.2. Parameter Optimization and Sensitivity Evaluation

We calculate the K, k and R value of the five parameters based on RA theory, which is listed in Table 5.

Table 5: The K / k values at different levels for different parameters. k_1^A is the average value of K_1^A.

Parameters	A	B	C	D	E
K_1	-5.09	-6.02	-3.30	-2.23	-0.81
K_2	-3.63	-1.85	-0.72	-0.60	-0.81
K_3	1.17	2.05	1.19	-0.38	0.23
K_4	4.16	3.42	1.79	1.74	0.91
K_5	3.39	2.40	1.05	1.47	0.48
k_1	-1.02	-1.20	-0.66	-0.45	-0.16
k_2	-0.73	-0.37	-0.14	-0.12	-0.16
k_3	0.23	0.41	0.24	-0.08	0.05
k_4	0.83	0.68	0.36	0.35	0.18
k_5	0.68	0.48	0.21	0.29	0.10
R	1.85	1.89	1.02	0.79	0.26

The relative size of full range R and the effect of each level on the experimental results are shown in Figure 3.

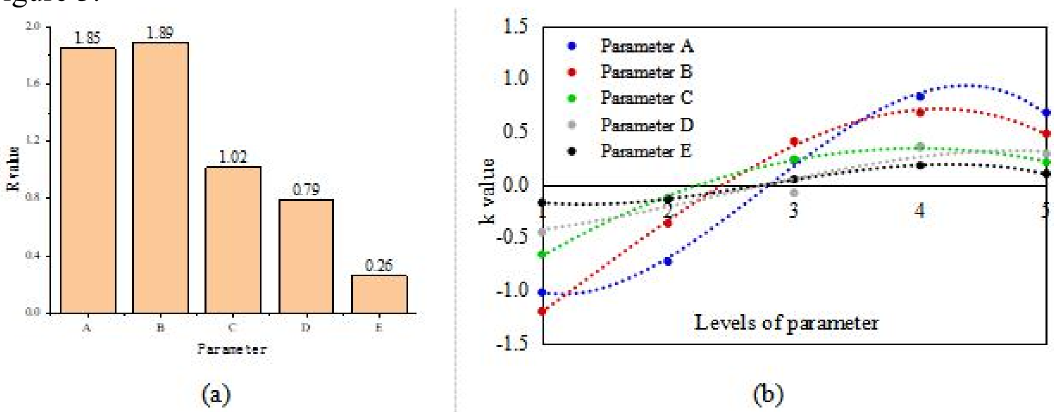


Figure 3: a. The sensitivity value R of parameters; b. and the trend of levels for parameter A to E.

Three conclusions can be made:

(1) The range $R_B > R_A > R_C > R_D > R_E$, as shown in Figure 3a, which means polymer injection volume and solution concentration are more sensitive in overall development effect.

(2) The effect of parameter A, B, C, E rises with their level change (Figure 3b), and each of them reaches a peak in this process, then sees a decrease afterward. The effect of parameter D increases as the level grows, but the growth trend is less significant.

(3) Based on the analysis and results above, the appropriate ranges of injection parameters for polymer flooding in this well group are obtained. In this well group, the optimized polymer solution concentration and molecular weight are 1550-1650mg/L and 22-24 million, the appropriate

parameters of polymer injection volume and speed are 0.7-0.8PV and 0.20-0.22PV/a respectively, and when the fw is higher than 80% and lower than 85%, the development effect is the best.

4. Conclusion

A comprehensive evaluation system of ten indicators is successfully established to assess the performance of polymer flooding. According to the distribution of principal components, the cumulative contribution rates of the first four reached 90%, indicating that this method is applicable to the evaluation system.

The optimal values of parameters are obtained through OED-PCA-RA method, which enable to achieve better development effect and provide a reference for polymer development oilfield to realize high efficiency polymer flooding development.

This workflow provided in this study can also applied in parameter optimization in other domains by designing different orthogonal experiments and changing the evaluation factors.

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