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A novel method applied to optimize oil and gas well working fluids

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Abstract—**The objective of this study is to introduce a new method applied for optimization of oil and gas working fluids. The multiple regression experimental design method (MRED) was based on the principle of multiple regression analysis, established the regression equation between test indicator and multi-factors, verified the regression equation with statistic test, set the precision and the optimal composition was found through trial calculation in the inverse model. MRED eliminate the human factor and show its universality in solving multi-factors problem. MRED was applied to optimize fuzzy ball drilling fluids which have density of 0.70 g/cm^3, 0.80 g/cm^3, and 0.90 g/cm^3, respectively and fuzzy Ball completion fluids which have viscosity of 24 mPa·s， density of 0.80 g/cm^3. The optimal formulas were obtained by using this method and successfully applied in working well.**

Index Terms—**multiple regression; inverse model; oil and gas wells, working fluids**

The drilling fluids are very important as blood in people's body in oil and gas drilling events. It is the key to choose drilling fluids' system and prepare drilling fluids with the ideal properties to successfully finish drilling wells and lowering the cost. The available formulas for oil and gas well drilling fluid can effectively guide the onsite construction, reduce or avoid accidents, increase work efficiency, shorten the drilling cycle and reduce the cost of drilling, as well as reduce pollution and increase production capacity. As a result, whether the drilling engineering can be successful or not is conditioned by the oil and gas well drilling fluid properties.

However, the composition co-effect is involved in drilling fluids system. Thus, a large number of experiments were demanded to find the relation between concentration of agent and performance of drilling fluids. Furthermore, it is difficult to find it due to the large number of components of drilling fluids. Besides, compared to true solution, the stability of performance was relatively poor because drilling fluids mostly belong to multi-phase fluid, suspend fluids or colloid. Therefore, many researchers used mathematical method to optimize formula of drilling fluids in order to reduce workloads and improve the precision of formula, etc.

Orthogonal experimental method is suitable for experimental design with multi-factor and multi-level. It is based on comprehensive test results to select representative data and conduct the tests. These representative data should be "uniform dispersion and homogeneous", namely the level of any column would appear and the times of appearance are equal, all possible combinations of any two columns between different levels would appear, and the number of occurrences are equal. In 1951, Taguchi Xuanich, famous statistician from Japan, invented orthogonal table with the combination selected from orthogonal test, Orthogonal experimental method can overcome disadvantage of large amount of tests compared to comprehensive test. HONG et al [1] (1982) initially applied the orthogonal experimental method to the drilling fluid design. The formula of free-solid drilling fluids was optimized by ZHANG et al[2] (2011) with orthogonal experimental method and formulas with optimal conductivity, apparent viscosity and value of losing water was obtained. However, the final formula obtained from this method perhaps was not the optimal, because it can only be one combination of forward test design. Besides, more types of treating agents, more workload and more time will be cost.

Similar to orthogonal experimental method, uniform design method set the test in terms of uniform table while selected combination was not homogeneous. Hence uniform design method needs less tests as well as the precision was limited. PENG et al [3] （2000）firstly introduce combined uniform design method with regression analysis to design drilling fluid And the result of optimization is relatively good. Uniform design method can reduce the amount of tests meanwhile had a good optimization result, but it is still not the best optimization model because of the limitation of amount level.

Considering more than one performance will be changed after adding one treating agent, the performance of drilling fluids should be evaluated comprehensively while data are complex. From this aspect, grey relational analysis solved the problem. WANG et al [4](1995) used grey relational analysis to select additives for drilling fluids in optimization of filtrations. Grey relational analysis is an important part of grey system. Calculate relational degree between performance of tested drilling fluids and ideal performance. The dose of treating agents was obtained according to relational degree. In the grey relational analysis, weight of factors depend on experience which make this method only suitable for experienced engineer meanwhile precision was limited.

With the development of computer technology and the exploration of knowledge, the technology which is able to extract potentially useful information and knowledge from massive and fuzzy random data appeared. This technology, called data mining method, is currently applied to eight kinds of analysis such as the association analysis, classification analysis, prediction analysis, cluster analysis, trend analysis and deviation analysis. The main methods applied in data mining are statistical analysis method, decision tree method, neural network method, genetic algorithm and rough set and visualization technology, etc. In drilling fluid formula optimization, data mining was mainly used for clustering analysis and forecast analysis with neural network. The data mining method was applied to drilling fluid formula design by ZHANG et al [5] (2008) and it was proved that the result is in accordance with laboratory drilling fluid formula optimization. Thus, data mining method can quickly get a desired formula design as long as the data base is large and reliable enough.

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However, regular methods like orthogonal experimental method, uniform experimental design, grey system and data mining method have some deficiencies such as large numbers of experiments, hard to analyze the experiment data, the unification of quantity degree and dimension etc. [6]. Some error cannot be avoided in regular optimization method. Multiple regression analysis was firstly introduced by YAN et al [7] (1986) to optimize the formulas of drilling fluids in China. Unfortunately, this paper didn't find the specific formulas but the function between the performance parameter of the working fluid and the concentration of agents. The weight of factor was decided artificially according to users' experience. Furthermore, despite relation between performance and concentration of drilling fluids was found, formula cannot be obtained through the regular method while finding the optimal formula is the ultimate goal. Based on the regression analysis, multiple regression experimental design method (MRED) was invented by LihuiLab to hurdle these disadvantages, hence it also called "Lihui-Lab method". The core of MRED is multiple regression analysis which is a mathematical statistics to deal with correlation between variables. It can find the best production conditions and the best solution through the establishment of mathematical models. The multiple regression experimental design for oil and gas well working fluid is a new method to find out the relation between the performance parameter of the working fluid and the additional dose of agents. It can also find out the best formula for the working fluid through mathematical models. MRED was firstly applied to optimize the formula with two agents [8] (ZHENG et al, 2005) and later was applied to the optimization of the cost controlling [9]. (ZHENG et al, 2005)

However, the result still cannot satisfy the requirement of engineering with many types of agents. During design of oil and gas working fluids, the dose and type of each treating agent should be obtained with the certain performance. Thus, a new effective high universality optimization method is urgently needed. Later MRED was improved by self-optimization theory and the MRED was developed. Self-optimization theory was proposed by Professor Zheng[10] (2005). According to self-optimization theory, the optimal fitting method and minimum error was selected by data itself. The weight of factor during test was expressed mathematically. Self-optimization theory eliminates the influence of human factor compared to other optimized method. The optimization of oil and gas working fluids with various treating agents was improved thanks to application of self-optimization on MRED. As a result, quantities of test reduced a lot.

This paper will tell the principle of MRED by carrying out the inverse model according to self-optimization theory. In the inverse model, precision control was achieved through setting the precision and taking all the composition back into forward model. MRED was applied to rheological research on the fuzzy ball drilling fluid by ZHENG et al [11] (2008) . Yang et al [12] (2014) applied MRED to optimize the viscosity, density and stable time of fuzzy ball diverting fracture fluids. The laboratory result showed the laboratory finding was consistent with calculated results. In spite of good application for MRED, it is still not applied in a wide scope. What's more, there's no complete introduction on principle of this method and its application was limited. Hence it is necessary to share the principle of MRED.

1. THE PRINCIPLE OF MRED

The drilling fluids agent types can be altered by the demand of drilling engineer. The ranges of concentration of commercial agents are arbitrarily selected within the recommended ranges. Then, a group of arbitrary formulas were designed. The drilling fluid systems can be prepared by arbitrary formulas and the systems properties were diagnosed. Through factors coding and test preparation, test data satisfied the requirement was selected. Assume that there is a function relation between the performance and dose of agents by using experimental data, the function is established by making a multiple regression analysis on the unspecified function. Analyze it mathematically and program the result. Statistic test is conducted to identify the equation and the optimal model was found after constantly adjusting and test. Generally speaking, it is acceptable that the correlation coefficient of the function should be above 0.95, and the error should be less than 5%. If not, it should be re-fitted. The optimized formulas was achieved by the trial calculation, which has enough accuracy within the given properties values. [13]. Besides experiments should be done to diagnose the formula. Finally, the optimal formula was obtained. The main procedure was showed as Fig.(1)

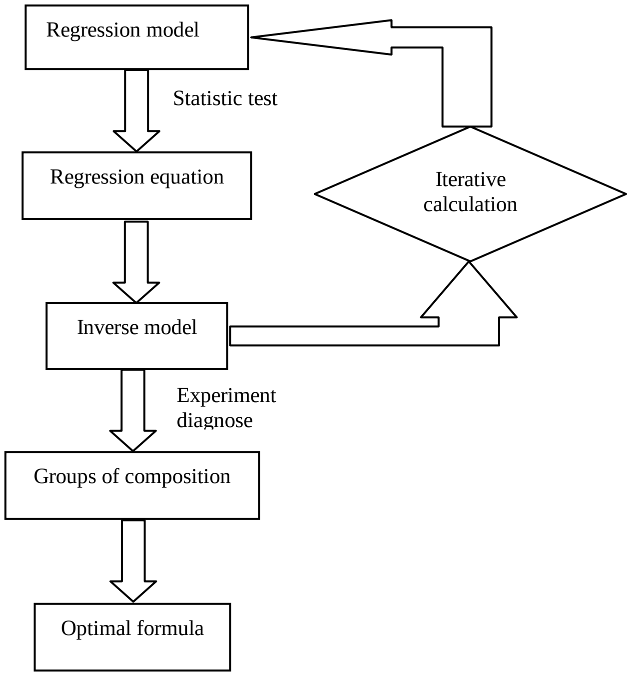

Fig.(1) schematic of MRED

1.1. Regression Model

Building regression model is the first step to apply MRED. Step was shown as follow ,

(1) According to the demand of drilling engineer, chose the drilling fluids agent types, the amount of agents, etc. And the doses of various agents are arbitrarily selected within the recommended ranges.

(2) Assume the function between performance parameter and treating agents of working fluids. The regression model can be divided into linear model and non-linear model. For instance, the multiple linear regression model with transaction was shown as follow,

$$\hat{y} = \hat{\beta}_0 + \sum_{j=1}^{p} \hat{\beta}_j z_j + \sum_{\substack{h<j \\ \lambda\in\lambda^*}} \hat{\beta}_{hj}^{(\lambda)} z_h z_j \qquad (1)$$

Where y is demanding performance parameter. $\hat{y}$ is the estimate value of demanding performance parameter ; z_1 , z_2 , … , z_p means the number of testing factor is p ,namely the amount of treating agents ; $\hat{\beta}_0$ and $\hat{\beta}_j$ are the estimating value of β_0 and β_j ,respectively , means the regression coefficient ; λ =1 , 2 , ... , λ^* , λ^* is the amount of interaction in the test ; $\hat{\beta}_{hj}^{(\lambda)}$ is the λ^{th} regression coefficient of first-level quadratic interaction term.

(3) Test factors coding. Confirm the range of each treating agents, and the limit of upper and lower is respectively z_{2j} and z_p , z_{0j} is the arithmetic mean value , the interval between each z_j is Δ_j , the test factors coding means perform the following linear transformation on the test factors:

$$x = \frac{z - z_0}{\Delta} \quad (2)$$

In order to keep the range of transformed factor between +1 and -1,build a one-to-one correspondence between x and z

(4) Plan preparation. Choose a reasonable test design table, usually there are comprehensive test, two-level orthogonal array, Hadamard matrix [14], etc. In addition, to facilitate the verification, zero point repeated test should be done.

(5) With least squares method, the regression coefficients can be obtain by making a multiple regression analysis on the unspecified function and establish the multiple regression equation:

$$\begin{aligned} y &= f(x_1, x_2, x_3 \cdots x_i) \\ &= b_0 + b_1 * x_1 + \cdots + b_i * x_i \\ &+ b_{i+1} * x_1^{\,2} + \ldots + b_{2i} * x_i^{\,2} \end{aligned} \quad (3)$$

This step can be realized by using computer software such as MATLAB[15]. (SU Jin-ming, 2004)

Noticeable, if amount of test data was more than composition of treating agents, all the possible combination of test data would be considered to fit the equation. The optimal regression model would be found according to error analysis. For example, there are five treating agents and 10 groups of test data, randomly selected 5 groups of test data fit the equation. Noticeable, all the possibilities should be considered, thus 252 regression equations would be built. Through coefficient of determination, optimal regression equation was found. In this way, no human factor was included, regression equation was established.

1.2. Statistic Test

After regression model was built, the regression model should be identified if it can correctly reflect the relationship between performance parameter and the amount of treating agents and if it is suitable for optimization. In this paper, test for regression model was divided into three parts. [16] Every part is equally important. The equation will be re-fitted if one part couldn't satisfy the requirement.

(1) Test of goodness of fit

The ratio of regression sum of squares to the total sum of squares was used to illustrate the fitting effect of regression model. R^2 was defined as coefficient of determination to examine the fitting effect.

$$R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \quad (4)$$

R^2 is a value between 0 and 1. Value of R^2 is closer to 1, the better fitting effect of data to regression model. In practice, the optimal model couldn't be found if it only relies on coefficient of determination, the influence of each variable on the dependent variable should be considered. R^2 could be obtained when used matlab find regression equation.

(2) The significance test of regression parameters. (Student's t test)

The significance test of regression parameters is aimed to verify if corresponding independent variable of each regression coefficient has significant effect to dependent variable.

$$t = \frac{\hat{\beta}_j - \beta_j}{Se(\hat{\beta}_j)} \sim t(n-k) \quad (5)$$

Set value significance level α , critical value $t_{\alpha/2}(n-k)$ could be obtained though checking t-distribution table. If $|t| \geq t_{\alpha/2}(n-k)$, it means the influence of independent variable was significant to dependent variable under significance level α , or it is not significant. Normally, the value of α was set to be 0.05. The reason might be too much error for the test and then the test should be re-done or the indicator barely has effect for the indicator, then the factor should be abandoned and re-fit the model.

(3) The significance test of regression parameters (F-test).

Although t-test has test the influence of independent variable on dependent variable, the influence of unit regression coefficient on regression equation since multiple regression model contained more than one independent variable.

$$F_f = \frac{S_f / f_f}{(S - S_f)/(f - f_f)} \sim F_\alpha(f_f, (f - f_f)) \quad (6)$$

If statistic value F_f is above critical value $F_\alpha(f_f, (f - f_f))$, the influence of on the indicator is significant under the α level, or the model should be re-fitted.

Through above test, when test error is properly controlled, all the regression coefficients have influence on the test indicators, model is in line with the actual, substitute the linear transformation formula into equation (3) and the value of $b_0, b_1 \cdots, b_i, b_{i+1}, \ldots b_{2i}$ is obtained, the final regression equation expression will be found. Calculate the correlation coefficient of the regression equation and residual analysis should be conducted. All the tests could be done with mathematical software.

1.3. Inverse model

Multiple regression analysis is usually based on a large number of experimental data. It is a process of finding the certain pattern through data processing in statistics. Since the error exist in both experimental data and multiple regression analysis, the data obtained from multiple regression analysis need further test. Going ahead, an inverse model was introduced to optimize given value of indicator. In the inverse model, we need to set precision at first. Taking all the composition back into the forward equation, the optimized compositions was achieved by the trial calculation, which has enough accuracy within the given properties values. Run the forward model with iterative method or the trial method. Then we can get a series of group formula which could reach the indicator. If data obtained was still too much, precision should be increased to achieve a better effect. On the contrary, if no formula was obtained under the certain precision, considering the requirement of the performance, precision can be adjusted.

In the inverse model, iterative method is the crucial part to realize precision control. It is a process to recursive new value from the old value constantly. Initial estimated value should be sure. The iterative formula can be built according to the regression equation from forward model. In terms of precision set before, iterative calculation was conducted and final result would satisfy the demand for accuracy. Iterative method found the target value through repeated calculation and it could find the solution directly. With the development of mathematic software, iterative method showed great advantage and become a regular method in finding the solution.

1.4. Formula diagnose

In the optimization of oil and gas working fluids, a series of treating agents group which can reach the requirement of oil and gas working fluids performance was achieved through MRED. Then experiments on every obtained formula would be needed in the lab. Compounded the composition in terms of formula in the lab and measure the performance parameters of all the formulas obtained. When error between the measured value and demanding performance value is less than 5%, then the treating agents were considered to be the formula satisfied the requirement, or abandon the group of composition. If laboratory finding is consistent with calculated results, the optimal formula will be selected according to the principle of lowest cost. If the laboratory finding is not consistent with calculated results, or the error between them is too much, the experimental group will be considered as basic test data to conduct multiple regression on test data.

2. CASE HISTORY

MRED were introduced to design density, plastic viscosity and other properties in Moxi gas field, Sulige gas field, Suizhong oil field. Application shows that the relative error between the target value of the drilling fluid system made up by the optimized formula and the given target value is within 5%, so the drilling fluid meets the needs of the work. It enormously decreases experimental times and enhanced experimental accuracy.

2.1. Case 1

The coal formation is easy to leak, the reservoir is more vulnerable with improper exploitation. Lost circulation prevention is more important in CBM exploitation. [17]

To prevent and plug the leaks automatically and effectively in down-hole operation, Zheng et al (2010) [18] developed a novel leak resistance material called fuzzy ball working fluid. Later, through laboratory rheological properties experiments, microstructure observation, plugging tests of fuzzy-ball working fluids, and field trials on depleted reservoirs, fuzzy-ball drilling fluids was proved to be a high-performance plugging fluid with high economic benefits. Under 1000-2000 microscope, diameter of fuzzy ball is 15-150 μm and the thickness is 3-10 μm. Since fuzzy ball drilling fluids contained a kind of spherical material which has the microstructure of "one core, two layers, and three membranes", it can change its size and shape according to the width of leakage paths as well as capacity working under high temperature and high pressure (HTHP). Through plugging experiment, microstructure observation and series application on test wells, found out the optimized fuzzy ball drilling fluids have good effect on plugging the leakage paths. [19]

Sun [20] (2014) proved that fuzzy ball drilling fluids can control leakage rate and solve serious leakage problems on pilot hole in raise boring. Following procedure shows the application of MRED on optimizing the viscosity of fuzzy ball fluids. It was applied to Moxi Gas Field where the middle section once stopped producing because of serious lost circulation. After fuzzy ball drilling fluids was selected to use under TD depth of 2,949 m and fuzzy ball drilling fluids density of 1.00-1.08 g/cm^3, no lost circulation. Fuzzy ball drilling fluids owning high-pressure bearing capacity and good lost circulation preventing ability under low porosity and low permeability was proved through analyzing down-hole density and field fuzzy ball drilling fluids .[21]CLH-04H is the first multi-branch well applying fuzzy ball drilling fluids. It cannot build the circulation under previous technology and drilling fluids. The original leakage rate of 40 m^3/h is reduced to less than 5 m^3/h after application of fuzzy ball drilling fluids. DFS-02-H2 is the first horizontal well applying fuzzy ball drilling fluids. Horizontal segment of 200 m under depth of 1275 m was not finished for 3 months because of lost circulation while it took 5 days to solve this problem by using fuzzy ball drilling fluids. [22] Furthermore, fuzzy-ball drilling fluids were applied to control lost circulation effectively for CBM in the Ordos Basin of China. [23] (Li Z C et al, 2013) Cui et al [24] (2013) prove the application on the third open of 12-11-3H well in Qinping. It took 3 days to accomplish drill depth of 4189.49 m. After fuzzy-ball drilling fluid was applied, the drilling rate was increased to 95%, average drilling rate was 12.65 m/h. Despite of effective application on oil field, the optimization of fuzzy ball drilling fluids was not proposed on these papers. MRED offers a new effective method to optimize fuzzy ball drilling fluids which will promote the application of fuzzy ball drilling fluids.

Well X is a horizontal production well with five designed branches, which is located in Ordos basin of China. In this area, the facture in coal seam is developed. During drilling, bentonite drilling fluids was used in the first spud. Air and clean water drilling fluids was used in the second spud. Each drilling finished well depth is 1900 m, 1900 m, 1862 m, 1815 m and 1678 m respectively. It is open hole completion. The stability was poor due to long open hole section soaked in the drilling fluids. In the course of drilling, lost circulation was serious. Hence fuzzy ball drilling fluids was used in the third section. According to the condition of Well X, the density of fuzzy ball drilling fluids should be 0.90-0.98 g/cm^3. MRED was applied to optimize fuzzy ball drilling fluids.

The ideal fuzzy ball drilling fluids consist of agent A, agent B, agent C, agent D, agent E and agent F. Arbitrarily selected the additional dose of A, B, C, D, E, and F within the range of the recommended amount. Design 17 groups of drilling fluids formula with different composition and measure plastic viscosity of each group. The plastic viscosity was set to be objective function, regression function between density and the additional dose of various agents was obtained, and the equation is:

$$\begin{aligned} y &= f(x_1, x_2, \cdots, x_7) \\ &= b_0 + b_1 x_1 + \cdots + b_7 x_7 + \\ & b_8 {x_1}^2 + \cdots + b_{14} {x_7}^2 \end{aligned} \tag{7}$$

Where y is density , $x_1, x_2, \cdots, x_6$ refer to A, B, C, D, E, and F separately , $b_0, b_1, b_2 \cdots b_{13}, b_{14}$ refer to regression coefficient , f is the function of plastic viscosity and amount of treating agents.

Based on given data, get the undetermined coefficients of b_i with least square method, substitute bi values in the equation (7), and we will get the quadratic function relation between the density and the additional dose of each agent:

$$
\begin{aligned}
y &= 4.5979 + 3.333x_1 + 1.6034x_2 \\
&-62.4924x_3 - 16.8323x_4 - 9.6012x_5 \\
&+7.7711x_6 + 0.1512x_5 - 15.6128x_1^2 \\
&-0.6443x_2^2 + 199.9308x_3^2 + 322.6138x_4^2 \\
&+19.3192x_5^2 - 17.8227x_6^2 - 0.0511x_7^2
\end{aligned} \tag{8}
$$

Through statistic test, get the model correlation coefficient R^2 = 0.9981 and the regression equation whose regression accuracy is over 0.95. The residuals plot was showed as Fig. (2).

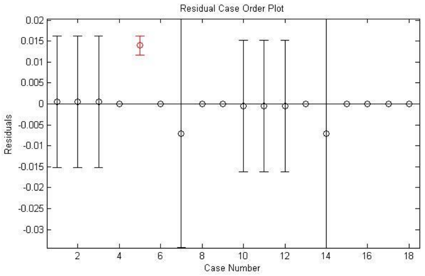

Fig. (2). residuals plot for equation (8)

The Fig. (2) shows that zero point was contained by confidence interval of all 17 fitting data except the fifth group which could be considered to be anomalous point. Through t-test, the value of $|t|$ are all above 0.6974. The value of F is 109.5748 which is above 2.37. Thus, both regression coefficient and equation are significant when confident degree is 0.95. Generally speaking, the regression model could reflect the relationship between treating agents and performance parameter.

In the inverse model, set the precision d=0.0003, 0.0001, 0.0003 and target value of plastic viscosity as 18, 20 and 22 mPa·s, respectively. After trial calculation, five groups of drilling fluids formulas were obtained. Randomly select two groups of formulas, give the feedback to the laboratory for further verification. Error analysis was showed in Table. (1).

Table. (1). Error analysis result

formula	Theoretical density (g/cm^3)	Actual density (g/cm^3)	Fractional error (%)
2#	0.7	0.72	2.78
7#		0.73	4.19
4#	0.8	0.77	4.00
7#		0.83	3.61
3#	0.9	0.86	4.65
6#		0.87	3.45

Find out the actual viscosity value are very close to expected value. Through error analysis, measurement error between theoretical and tested density value was obtained. The results proved that the fractional errors between theoretical values and tested values are all less than 5%, therefore, the regression model is applicable in optimizing fuzzy ball drilling fluids.

In this way, five branches were successfully drilled to designed well depth without leakage. During drilling, the density was adjusted according to specific condition. In this case, the fuzzy ball drilling fluids have density of 0.90-0.98 g/cm^3, funnel viscosity of 30-40 s, plastic viscosity of 10-14 mPa.s and yield point of 7.5-11 Pa. In this section, the optimized fuzzy ball drilling fluids showed its good carrying capacity and suspending performance. ROP is 7.5 m^3/h and leakage rate was 0.5-1.0 m^3/h.[25]

In this case, optimization of oil and gas drilling fluids was conducted with orthogonal experimental method and uniform method. The experiment times and foundation of weight of factor were showed in Table. (2).

Table. (2).comparision of methods

Experimental method	Experiment times	Weight of factor
Orthogonal experimental design	36	Range analysis based on experiments
Uniform experimental design	24	Experience based on experiments
MRED	18	Test data

2.2. Case 2

As stated earlier, fuzzy ball working fluids was applied to oil and gas wells plugging lost circulation and the results were great. It is proved to be able to plug the leak passages dynamically without anticipating the location of the lost circulation and how serious it is. [18] During petroleum engineering, lost circulation is a common problem so that well completion is an important part. Since workover fluid was contacted with formation directly, a new self-matching, with less damage temporary plugging material is desperately needed during petroleum engineering. Yang et al [26] (2013) proposed that the main ingredient of the fuzzy ball is vegetable gelatin and cellulose, so it is environmentally safe. This paper also proposed three methods in dumped fuzzy ball material recycling. Compared with gas containing working fluids, besides the high pressure bearing capability, the preparation of the fluid is proved to be rather simple and less damage on the formation was proved by the application in the field. Because of these characteristics, fuzzy ball is an ideal material as the workover fluids. [27] Based on the experimental data, the optimization model of fuzzy ball workover fluid in terms of viscosity and density was established.

Fuzzy ball workover fluid consist of agent A, agent B, agent C, agent D and small amounts of other additives. Arbitrarily select the additional dose of agent A, B, C, D within the framework of the recommended amount. 21 groups of drilling fluids formula were compounded with different composition and measure viscosity, density and stable time of each group. Viscosity was set to be objective function between viscosity and the selected treating agents:

$$
\begin{aligned}
\mu &= f(x_1, x_2, x_3, x_4, x_5) \\
&= b_0 + b_1x_1 + \cdots + b_5x_5 \\
&+ b_6x_1^2 + \cdots + b_{10}x_5^2
\end{aligned} \tag{9}
$$

Where μ stands viscosity, $x_i\,(i=1,\ 2,\ 3,\ 4)$ stands the amount of agent A, B, C and D of fuzzy ball fracture diverting fluids respectively, f is the function between viscosity and each treating agents of fuzzy ball fracture diverting fluids , b_0 is intercept, b_i is the coefficient of x_i .

Chose 19 groups of formula and using the Regress toolkit of MATLAB software, all the coefficients could be calculated automatically. Established the function between viscosity and the amount of fuzzy ball fracture diverting：

$$\mu = -18.6538x_1 - 9.8558x_3 - 201.7308x_4 + 331.75x_5 + 74.0385x_1^2 + 0.0808x_2^2 + 626.4423x_4^2 - 814.3269x_5^2 + 8.0538 \tag{10}$$

Through statistic test, find the coefficient of regression function is R^2 =0.9182. The residuals plot was showed as Fig. (3).

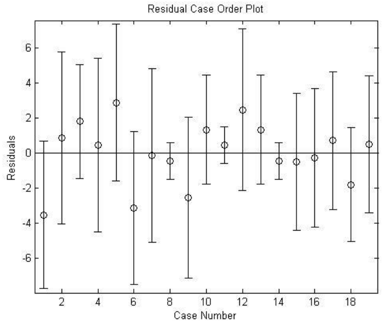

Fig. (3). residuals plot for equation (10)

The Fig. (3) shows that zero point was contained by confidence interval of all 19 fitting data and no anomalous point was appeared. Through t-test, the value of $|t|$ are all above 0.6924. The value of F is 10.1369 which is above 2.39. Thus, both regression coefficient and equation are significant when confident degree is 0.95. Generally speaking, the regression model could reflect the relationship between treating agents and performance parameter.

Similar to the establishment of the viscosity function, the regression model for density was established. The regression function was showed as follows.

$$\rho = -1.3279x_1 + 1.2550x_3 + 3.2894x_4 - 6.1829x_5 - 1.8413x_1^2 + 0.0491x_2^2 - 9.0745_4^2 + 13.0069x_5^2 + 1.0702 \tag{11}$$

Through statistic test, find the coefficient of regression function is R^2 =0.8902. The residuals plot was showed as Fig. (4).

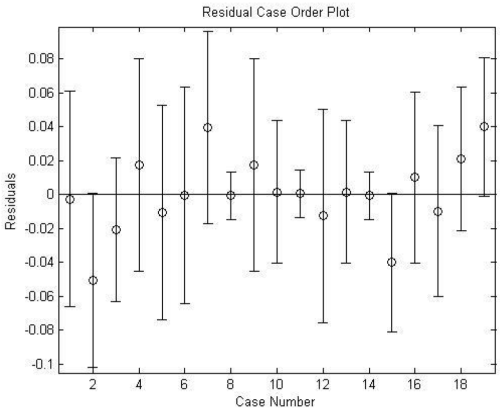

Fig. (4). residuals plot for equation (11)

The Fig. (4) shows that zero point was contained by confidence interval of all 19 fitting data and no anomalous point was appeared. Through t-test, the value of $|t|$ are all above 0.6924. The value of F is 10.1369 which is above 2.39. Thus, both regression coefficient and equation are significant when confident degree is 0.95. Generally speaking, the regression model could reflect the relationship between treating agents and density.

The built optimization model was applied to find the composition of the workover fluid with the viscosity of 20 mPa·s, density of 0.80 g/cm^3. In this experiment, search error was defined to control the precision. It should be larger than maximum model error in case of losing true results. The search errors were set as 1.0 mPa·s, 0.5 g/cm^3. Run the inverse model, three compositions were obtained by the model. Compound all three compositions in the lab, and the viscosity, density and stable time were all measured.

Table. (3). Error analysis result

formula	Actual density（g/cm^3）	Fractional error（%）	Actual viscosity (mPa・s)	Fractional error（%）
1#	0.83	3.33	21	5.00
2#	0.82	2.50	19	5.00
3#	0.79	1.25	19	5.00

The maximum relative error was found to be 5.0%. The compositions obtained by the present model agree well with the objective viscosity and density.

In this case, orthogonal experimental design and uniform experimental design were also conducted to optimize the fuzzy ball workover fluids. The test times and the foundation of weight of factors were showed in Table. (4).

Table. (4). comparison of methods

Experimental method	Experiment times	Weight of factor
Orthogonal experimental design	18	Range analysis based on experiments
Uniform experimental design	15	Large amount of experiments
MRED	11	Test data

The optimized fuzzy ball workover fluid was applied to Well X60. Well X60 is located in Jidong oil field Two oil layers in Well X60 have permeability of 248.7×10^{-3} and 154.79×10^{-3} μm^2 and a pressure coefficient of 0.73. At first, saltwater polymer drilling fluids was used and 1724 m^3 was lost into formation in all. Perforation couldn't be conducted due to serious lost circulation, after cement with walnut shell powder cement slurry was used and screen pipe run. In order to solve this problem, squeeze 15 m^3 fuzzy ball workover fluids with density of 0.9 g/cm^3. The problem of leakage disappeared after 45 m^3 fuzzy ball workover fluid was circulated. Application of fuzzy ball workover fluids on well workover and result showed the effect of optimization was good.

Besides application on fuzzy ball drilling fluids and fuzzy ball completion fluids, MRED also was applied to optimize cementing pad fluid. Practice of optimized fuzzy ball cementing pad fluid on Naiman zone well N-X-Y proved that the problem of cement slurry leakage was solved. [28] Well NAI1-X-Y is a directional well in old oil field with pressure parameter of 0.95. Reservoir leaked and the quantity of cementation was poor so that well test operation couldn't be conducted normally. Optimized fuzzy ball completion fluid with density of 1.20 g/cm^3 was used to plug leakage formation. Results showed the pressure bearing capacity of formation was improved, then cementation operation was completed smoothly with regular cement slurry.

CONCLUSIONS AND DISCUSSION

Through mathematical analysis and statistic test, it is proved that MRED is feasible theoretically. The optimal regression model was found based on multiple regression analysis and statistic test, the precision of optimization was improved by building the inverse model. Besides, MRED was proved to be practical by some cases. It was applied to optimize plastic viscosity of fuzzy ball drilling fluids and viscosity, density and stable time of fuzzy ball fracture diverting fluids in the lab. The multiple regression experimental design for oil and gas well working fluid has five principal advantages:

(1) MRED can work out specific formula with less quantities of tests compared with regular optimization method. Not only the relation between performance and concentration of agents was obtained, but also the specific formula was found. It takes the least amount of tests to find the optimal formula.

(2) MERD is fit to optimize oil and gas working fluids no matter how many types of agents. During petroleum engineering, different formation needed different oil and gas working fluids with different performance. Meanwhile, MRED is suitable to optimize oil and gas working fluids with multiple agents. MRED is the most suitable method in allusion to the design of oil and gas fluids.

(3) MRED eliminate human factor. Based on self-optimization, the weight of factor was selected by test data without interruption of human. In the course of the experiment, arbitrarily select the additional dose of agents within the framework of the recommended amount, and then various formulas meeting requirements can be got by the mathematics approach.

(4) MRED is suitable for optimization of drilling fluids, workover fluids, etc. Optimization on fuzzy ball drilling fluids and fuzzy ball completion fluids showed MRED is suitable to all the oil and gas working fluids.

(5) MRED is convenient to optimize oil and gas working fluids. Both the procedure and principle are relatively easy to understand, especially for the fresh men who don’t have experience. It needn’t understanding of advanced mathematical theory. The procedure is clear and effective.

Of course , problems still exist and discussion is necessary.

(1) The development of MRED had to combine with computer technology. Quantitative analysis was introduced by MRED with computer and mathematical method. Computer technology needs to be improved to reduce workloads.

(2) More advanced software was needed to improve operating rate and realize self-optimization. In the course of application of MRED, mathematical software was needed to support the efficiency. In above cases, MATLAB was used to fit equation and conduct iterative calculation as well as statistic test. However, it couldn’t realize large amount of calculation.

(3) This paper only applied multiple linear regression method. Actually, based on the principle of MRED, more fitting methods might be able to optimize oil and gas working fluids with less error, such as BP neutral network. In addition, MRED is a simple application of self-optimization theory. More method based on self-optimization could be used to improve the precision during optimizing oil and gas working fluids.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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