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Study on the methods screening profile controlling and flooding injection wells for heterogeneous mid-low permeability reservoir

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Abstract. In this paper, the screening indicators such as permeability variation coefficient, water absorption profile variation coefficient and permeability of profile controlling and flooding injection wells were first determined by a qualitative analysis. Secondly, in allusion to the heterogeneous mid-low permeability reservoir of oilfield D, the limits of the evaluation grades of the three screening indicators were determined with indoor physical simulation method. Finally, the grades of the profile controlling and flooding feasibility of the injection wells were evaluated using variable fuzzy sets based comprehensive evaluation method; then, a practical calculation was conducted by taking an injection well developed with water flooding for example; the calculation result showed that the method was easy to operate, reasonable to calculate, and could get reliable results; it could provide a decision-making basis for the implementation of profile controlling and flooding in the heterogeneous mid-low permeability reservoir of oilfield D.

Key words. Heterogeneity; Mid-low Permeability Reservoir; Profile Control and Displacement; Screening Methods.

1. Introduction

As water-soluble polymers as well as their gels were used in oil fields in the 1970s, Chinese profile controlling and water plugging technology entered a new stage of development, while block profile control decision-making technology was a subsequently developed supporting technology. Currently, the frequently applied block profile control decision-making technologies include PI decision-making technology [1], RE decision-making technology [2-3], RS decision-making system [4], and RMF decision-making method [5]. In the past, RE decision-making technology was mostly

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used in the overall profile control and screening of blocks: mainly based on the factors such as injection well's permeability, water injection profile, injection dynamics, and pressure drop at the wellhead, the decision factors of these parameters were calculated, and thus the best well was selected for profile control [6]. However, this method as well as screening parameters was not suitable for screening the injections well for profile control and displacement in heterogeneous mid-low permeability reservoir; in order to solve this problem, from the deep profile control and displacement mechanism in mid-low permeability reservoir, this paper studied a reliable and practical method screening and evaluating oilfield D by combining the geological characteristics of oil deposits of oilfield $D$and applying laboratory experimental method, so as to provide a decision-making basis for the implementation of profile control and displacement in heterogeneous mid-low permeability reservoir of oilfield D and also a technical support for the formulation of a highly efficient profile control and displacement plan.

2. Screening indicators of profile controlling and flooding injection wells

Weak gel in profile controlling and flooding process can simultaneously control and flood water. Evaluation on the profile controlling and flooding effect of an injection well mainly depends on its "flooding" effect. The injected profile controlling and flooding system preferentially enters the high permeability layer; after gelling it forced the subsequent fluid flow to turn to the mid-low permeability layer; therefore, the improvement effect of weak gel on the injection well profile was stronger as the heterogeneity of the reservoir was higher. Therefore, in this paper, permeability variation coefficient and water absorption profile variation coefficient were used as the evaluation indexes reflecting the reservoir heterogeneity. In addition, there were large molecular polymers in the profile controlling and flooding system and therefore it could only pass through a corresponding porous medium; for this reason, the feasibility of the reservoir's profile controlling and flooding was necessarily taken into account when profile controlling and flooding injection wells were screened.

3. Study on the level limits of the selection indicators of profile controlling and flooding injection wells

3.1. Study on the level limit of permeability variation coefficient

3.1.1. Experimental conditions

(1) A man-made three-layer heterogeneous rectangular rock core (45mm × 45mm × 300mm) was used as the experimental model; the gas permeability ratio was about $300\times10^{-3}\mu\text{m}^2$; permeability variation coefficient was about 0.4, 0.5, 0.6, 0.7 and 0.8 respectively.

(2) The crude oil in oil field D was applied to the experiment; after it was

dehydrated and filtered, kerosene was added into it, and then the simulation oil for experimental purpose was prepared according to the viscosity of the in-place oil: the viscosity was 4.9mPa·s under the condition of 47.5^{o}C.

(3) The synthetic brine prepared per the reservoir water salinity 8200 mg/L of oil field $D$was the experimental saturated core water; both preparation water and core controlling and displacement water were the return water of field $D$and the salinity was 4500mg/L.

(4) The experimental agents included 12 million polymer, composite ionic crosslinking agent and stabilizer.

(5) The experimental equipment included thermostat, constant speed constant pressure pump, high pressure intermediate container, manual metering pump, liquid production measuring tube, vacuum pump and pressure gauge.

(6) The experimental temperature was 47.5 ^{o}C.

3.1.2. Experimental steps

(1) After the model was evacuated for 6 hours, the synthetic salt water was saturated to measure the pore volume and porosity.

(2) The model was placed in constant temperature box for more than 12 hours.

(3) The oil was saturated until it filled the exit of the model and the water did not flow out, so as to determine the original oily saturation degree

(4) The water was flooded to the exit of the model per the displacement velocity of 0.3mL/min and the containing moisture took up 98%; the recovery rate in the water flooding period was calculated.

(5) 0.2pv composite ionic weak gel system (polymer concentration 800mg/L, crosslinking agent concentration 1800mg/L, and stabilizer concentration 200mg/L) was speedily injected per the rate of 0.3ml/min, and the recovery rate in the profile controlling and flooding period was calculated.

(6) The subsequent water was flooded to the exit of the model and the containing moisture was more than 98%, and the final recovery rate was calculated.

2.1.3 Experimental results and analysis

According to the reservoir characteristics of oil field, the heterogeneous rectangular rock cores of five different permeability variation coefficients were made, and the deep profile controlling and flooding experiment of weak gel was conducted according to the above experimental steps, so as to research the effect of different permeability variation coefficient on profile controlling and flooding. The basic parameters of the five cores were shown in table 1, and the recovery values of each stage were calculated; the experimental results were shown in table 2.

Table 1. The basic parameters of the five cores in different permeability variation coefficient

Core No.	Permeability variation coefficient	Permeability combination ($\times$10-3μm2)	Permeability ($\times$10-3μm2)	Original oily saturation (%)
FB-1	0.41	150-300-450	298	62.5
FB-2	0.49	150-250-500	302	63.6
FB-3	0.58	100-300-500	310	62.81
FB-4	0.68	50-300-550	308	63.5
FB-5	0.82	50-200-600	305	63.9

Table 2. The heterogeneous core oil displacing effect in different permeability variation coefficient

Core No.	Variation coefficient	Stage oil recovery ratio (%)			Ultimate recovery factor (%)	Improved recovery efficiency after Controlling and flooding (%)
		Water flooding	Controlling and flooding	subsequent water flooding		
FB-1	0.41	46.78	2.53	3.08	52.39	5.61
FB-2	0.49	44.76	2.71	4.84	52.31	7.55
FB-3	0.58	43.28	3.29	5.35	51.92	8.64
FB-4	0.68	41.45	3.68	6.08	51.21	9.76
FB-5	0.82	40.21	3.75	6.13	50.09	9.88

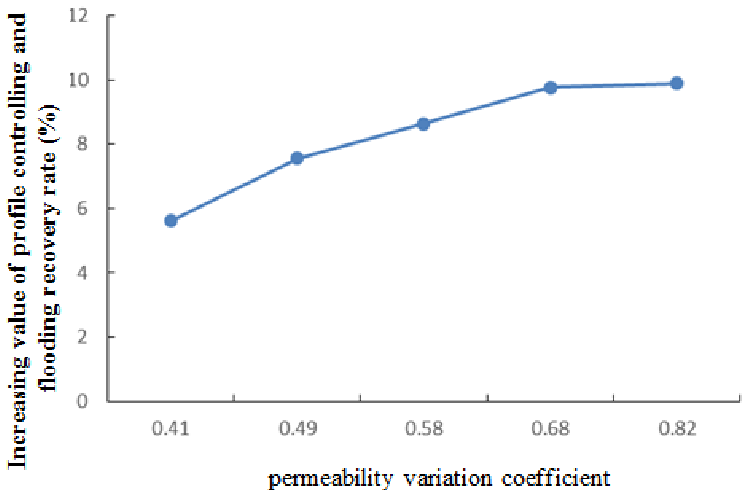

Fig. 1. the curve of the relations of profile controlling and flooding recovery rate with the permeability variation coefficient

Seen from Fig.1, the profile controlling and flooding recovery rate increased with the increase of permeability variation coefficient; the increase rate was faster first and then slower and reached the maximum at 0.5, and became very low to flat when the variation coefficient was greater than 0.7, mainly because the viscosity of the profile controlling and flooding coefficient could guarantee the oil flooding system expansion as well as the volume capacity and the profile controlling and flooding recovery rate continued to increase. However, due to the large difference between layers, the recovery rate increased slowly.

Therefore, the optimum range of the permeability variation coefficient of the selected profile controlling and flooding well was 0.5∼0.7, the profile controlling and flooding effect ranked second if the coefficient was larger than 0.7 and the effect was the worst if the coefficient was less than 0.5.

3.2. Study on the level limit of water injection profile variation coefficient

3.2.1. Experimental conditions

(1) The artificial homogeneous rectangular core (45mm×45mm×300mm) was used as the experimental model; a total of 30 pieces of artificial homogeneous rectangular cores were used for 15 groups of 3-tube parallel core oil displacement experiment, and the basic parameters of 6 cores were shown in table 4-5.

(2) Other experimental conditions were the same as 2.1.1.

3.2.2. Experimental steps

(1) After the model was evacuated for 6 hours, the synthetic saline was saturated to measure the pore volume and porosity;

(2) The model was placed in incubator at 47.5° for more than 12 hours;

(3) Water phase permeability was measured through water flooding;

(4) The oil was saturated to the exit of the model until it filled the exit of the model and the water did not flow out, so as to measure the original oily saturation degree;

(5) The water was flooded to the exit of the model per the displacement velocity of 0.3mL/min and the containing moisture took up 98%; the shunt volume of the three tubes was recorded respectively;

(6) 0.2pv composite ionic weak gel system (polymer concentration 800mg/L, crosslinking agent concentration 1800mg/L, and stabilizer concentration 200mg/L) was speedily injected per the rate of 0.3ml/min; the shunt volume of the three tubes was recorded respectively;

(7) The subsequent water was flooded to the exit of the model and the containing moisture was more than 98%; the shunt volume of the three tubes was recorded respectively.

3.2.3. Experimental results and analyses

By using the shunt data measured with 15 groups of three-tube parallel core profile controlling and flooding experiment, the shunt fraction rate of the three tubes in each group of experiment was calculated respectively; it was consistent with the calculation method of the injection well single-layer water absorption percentage in the actual field test; therefore, in the experiment, the variation coefficient calculated by the fractional flow rate could represent the profile variation coefficient, and the decreasing amplitude of the variation coefficient before profile controlling and flooding was used to characterize the profile improvement effect; the experimental result was shown in Fig.2.

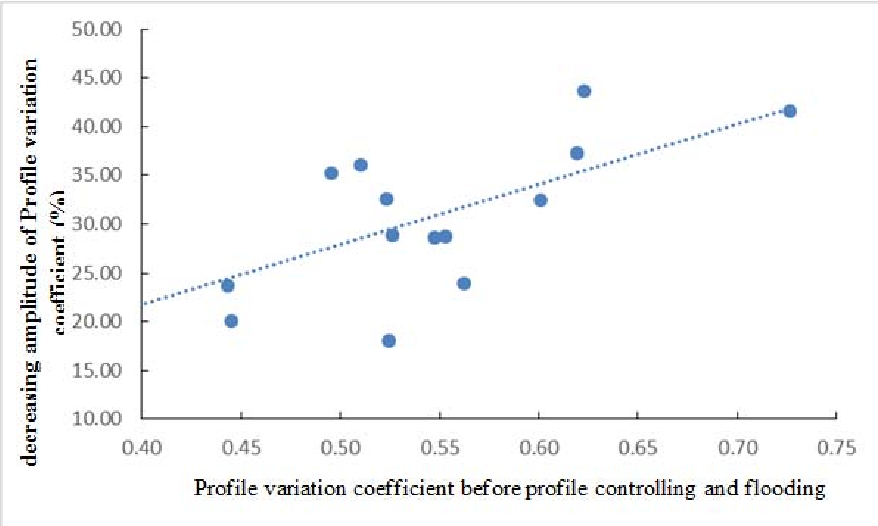

Fig. 2. the relation of the profile variation coefficient with the decreasing amplitude of the variation coefficient before profile controlling and flooding

Seen from Fig.2, the water absorption profile variation coefficient and decreasing amplitude fell into a direct ratio relation before profile controlling and flooding; the overall trend was "the water absorption profile after profile controlling and flooding was improved better if the water absorption profile variation coefficient before profile controlling and flooding"; the injection well water absorption profile of variation coefficient less than 0.5 before profile controlling and flooding was improved badly; the injection well water absorption profile of variation coefficient less than 0.6 was improved well.

Therefore, the optimal range of the water absorption profile variation coefficient of the selected well for profile controlling and flooding was greater than 0.6, followed by 0.5~0.6, and <0.5 was the worst.

3.3. Study on the level limit of permeability

3.3.1. Experimental conditions

(1) Artificial homogeneous cylindrical core (Φ5mm $\times$100mm) was used as the experimental model, and the gas permeability was $62\times10^{-3}\mu m^2$, $103\times10^{-3}\mu m^2$, $192\times10^{-3}\mu m^2$, $307\times10^{-3}\mu m^2$, and $394\times10^{-3}\mu m^2$;

(2) Other experimental conditions were the same as 2.1.1.

3.3.2. Experimental steps (1) After the model was evacuated for 6 hours, synthetic brine was saturated to measure pore volume and porosity;

(2) The model was placed in incubator at 47.5° for more than 12 hours;

(3) The oil was saturated to the exit of the model but the water did not flow out, so as to measure the original oily saturation degree;

(4) Water flooding was conducted per the velocity of 0.1ml/min; after differential pressure was stabilized, the differential pressure on both ends of the cores was recorded as Δp_b;

5) Composite ionic weak gel system (polymer concentration 800mg/L, crosslinking concentration 1800mg/L, and stabilizer concentration 200mg/L) was injected per the velocity of 0.1ml/min; after differential pressure was stabilized, the differential pressure on both ends of the cores was recorded as Δp_n;

(6) Water flooding was conducted per the velocity of 0.1ml/min; after differential pressure was stabilized, the differential pressure on both ends of the cores was recorded as Δp_a.

3.3.3. Experimental results and analysis

The injection performance of the profile controlling and flooding system could be evaluated through drag coefficient and residual resistance coefficient. Drag coefficient was numerically equal to the ratio of water fluidity coefficient and profile controlling and flooding system solution mobility, and it reflected the flowing capacity of the polymer in the profile controlling and flooding system to weaken the system; residual resistance coefficient was numerically equal to the ratio of permeability measured with saline water when the profile controlling and flooding system solution passed through the core, and it reflected the capacity of the system solution to reduce the permeability of porous media.

Known from the definitions of Darcy's formula, drag coefficient and residual resistance coefficient, the equation of drag coefficient and residual resistance coefficient can be converted into pressure difference ratio in indoor experiment; the formula was as follows:

Drag coefficient:

$$F_r = \Delta P_n / \Delta P_b \,. \tag{1}$$

Residual resistance coefficient:

$$F_{rr} = \Delta P_a / \Delta P_b \,. \tag{2}$$

Where,

ΔP_b —differential pressure on both ends of the core during the water flooding period before the profile controlling and flooding system was injected, MPa;

ΔP_n —differential pressure on both ends of the core when the profile controlling and flooding system was injected, MPa;

ΔP_a —differential pressure on both ends of the core after the profile controlling and flooding system was injected, MPa.

According to the above experimental steps, the drag coefficient and residual resistance coefficient of the homogeneous cores of different permeability were measured respectively, as shown in Fig.3.

Seen from Fig. 3, the profile controlling and flooding system had the ability to increase the flow resistance of water and reduce the permeability of porous media.

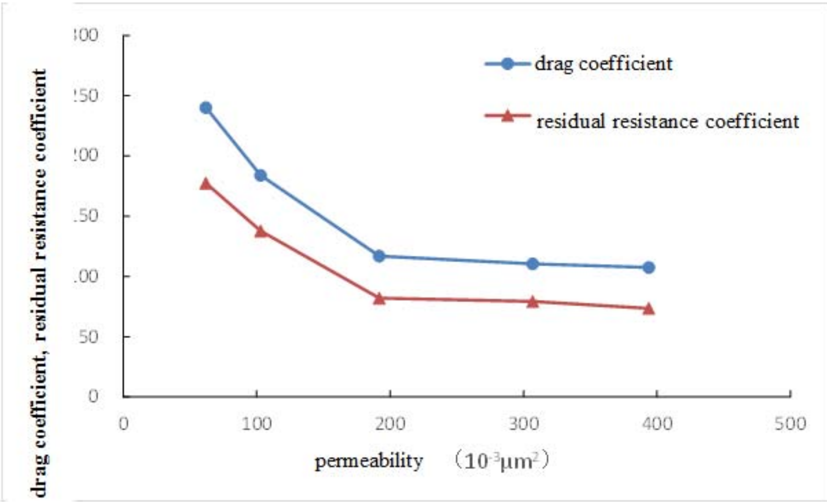

Fig. 3. the curve of drag coefficient and residual resistance coefficient to change with the permeability

With the decrease of permeability, drag coefficient and residual resistance coefficient gradually increased; when the permeability was less than 100×10-3μm2, drag coefficient and residual resistance coefficient increased greatly. This showed that the injection capacity and fluidity of the profile controlling and flooding system were poor in the reservoir of permeability less than 100×10-3μm2, thus giving rise to oil layer bridging. For this reason, through the experimental study, it was concluded that the profile controlling and flooding system's optimal permeability range suitable for the reservoir was greater than 100$\sim$ 300$\times 10^{-3}\mu$m^2, followed by $300 \times 10^{-3}\mu$m^2, and the worst was less than $100\times 10^{-3}\mu$m^2.

4. Study on the methods screening profile controlling and flooding injection wells

4.1. Comprehensive evaluation method based on variable fuzzy set

Combined with the screening characteristics of the profile controlling and flooding injection wells and considering the strong subjectivity of the membership function in the traditional fuzzy comprehensive evaluation method, the effect of different membership function combinations on the evaluation results was larger. Therefore, in this paper, the application of variable fuzzy sets based comprehensive evaluation method was actually based on the theory of variable fuzzy sets created by professor Chen Shouyu [6$\sim$7], and possessed the advantages such as simple calculation process and reliable results in comparison with other evaluation methods.

The steps of variable fuzzy sets based comprehensive evaluation method were shown as follows:

(1) Determining the set of evaluation factors and the set of comments

It was assumed that $x = \{x_1, x_2, \cdots, x_n\}$ was a factors set consisting of m evaluation indexes; $v = \{v_1, v_2, \cdots, v_c\}$ was a comments set consisting of c

comments. In this paper, the evaluation levels were good, medium, and poor respectively, and therefore $c = 3$ was established.

(2) Determining the standard interval of evaluation indexes

The matrix of the index intervals of multiple levels $h = 1, 2, \cdots, c$ and multiple indexes $i = 1, 2, \cdots, m$ was determined as follows:

$$\begin{bmatrix} a_{11} < a_{12} & [a_{12}, b_{12}] & \cdots & b_{1(c-1)} < b_{1c} \\ \cdots & \cdots & & \cdots \\ a_{m1} < a_{m2} & [a_{m2}, b_{1m2}] & \cdots & b_{m(c-1)} < b_{mc} \end{bmatrix},$$

or

$$\begin{bmatrix} a_{11} > a_{12} & [a_{12}, b_{12}] & \cdots & b_{1(c-1)} > b_{1c} \\ \cdots & \cdots & & \cdots \\ a_{m1} > a_{m2} & [a_{m2}, b_{1m2}] & \cdots & b_{m(c-1)} > b_{mc} \end{bmatrix},$$

Where, a_{ih} and b_{ih} were the upper and lower limits of the standard interval of the ith index to the lever h respectively; $a_{ih} < b_{ih}$ meant the smallest and optimal index, and $a_{ih} > b_{ih}$ was the biggest and optimal index.

The standard value at all levels of evaluation index was M_{ih}: it was the characteristic value (=1) of the ith index's relative membership degree to the level h, and the calculation formula was as follows:

$$\begin{cases} M_{i1} = a_{i1} & h = 1 \\ M_{ih} = \frac{c-h}{c-1} a_{ih} + \frac{h-1}{c-1} b_{ih} & h = 1, 2, \cdots, (c-1) \\ M_{ic} = b_{ic} & h = c \end{cases} \tag{3}$$

(3) Determining the index x_i's relative membership degree to level h

It was assumed that $r_h(x_i)$ was evaluation index x_i's relative membership degree to evaluation level h; the following formula could be established according to the unity of opposites:

$$r_h(x_i) + r_{h+1}(x_i) = 1\,. \tag{4}$$

Evaluation index x_i's relative membership degree to evaluation level less than level h or larger than level $(h+1)$ was 0.

If evaluation index x_i fells in interval $[M_{ih}, M_{i(h+1)}]$, x_i's relative membership degree to evaluation level h was as follows:

$$r_h(x_i) = \frac{M_{i(h+1)} - x_i}{M_{i(h+1)} - M_{ih}} \qquad h = 1, 2, \cdots, c-1\,. \tag{5}$$

(4) Determining index weight vector

As the importance degree of each evaluation factor in evaluation target was different, the weight of each factor was necessarily determined: weight vector was $w = \{w_1, w_2, \cdots, w_m\}$, in which $w_i > 0$ and $\sum_{i=1}^{m} w_i = 1$.

In this paper, the weight of each evaluation index was determined using combination determining weights method, and the specific method and practice were introduced as follows.

(5) Determining the comprehensive relative membership degree of level h

Formula (5-3) was a comprehensive relative membership degree model of a single index to level h; what this paper studied was a multi-index comprehensive evaluation issue, and evaluation object u was a comprehensive relative membership model to level h:

$$v_h(u) = \frac{1}{1 + \left\{ \frac{\sum_{i=1}^{m}[w_i(1-r_h(x_i))]^p}{\sum_{i=1}^{m}[w_i r_h(x_i)]^p} \right\}^{\frac{\alpha}{P}}} \tag{6}$$

Where,

α —optimization criterion parameter;

P—distance parameter;

$\alpha = 1$—least one-power criterion;

$\alpha = 2$—-least two-power criterion;

$P = 1$—Hamming distance;

$P = 2$—Euclidean distance.

Therefore, the two parameters had four types of combination of values; a linear model ($\alpha = 1$, $P = 1$) was generally applied for the calculation. In this paper, in order to make the calculation result more accurate and reliable, formula (6) was used to respectively calculate the comprehensive relative membership degree $v_{kh}(u)$ of four groups of parameter combinations, so as to constitute a comprehensive relative membership degree matrix $[v(u)]_{kh}$, in which $k = 1, 2, 3, 4$, $h = 1, 2, \cdots, c$, and the matrix after the normalization of row vectors was $[v^0(u)]_{kh}$.

(6) Calculating the level characteristic value of all levels

The level characteristic value formula was as follows:

$$H(u) = \sum_{h=1}^{c} v_h^0(u) * h \qquad (h = 1, 2, \cdots, c)\,. \tag{7}$$

Where,

$v_h^0(u)$—the normalized vector value of relative membership degree $v_h(u)$.

According to formula (7), the level characteristic value $H_k(k = 1, 2, 3, 4)$ could be calculated, and then their mean value could be calculated as the comprehensive relative membership degree of comprehensive evaluation object u to level h:

$$\overline{H} = \frac{\sum_{i=1}^{4} H_k}{4} \tag{8}$$

(7) Deciding grade of membership

According to the variable fuzzy evaluation criterion, the membership level of the evaluation object u was evaluated; the criterion was as follows:

$$1.0 \le \overline{H} \le 1.5, \text{assigned to level 1}$$
$$h - 0.5 \le \overline{H} \le h, \text{assigned to level } h, \text{ close to level } (h-1)$$
$$h \le \overline{H} \le h + 0.5, \text{assigned to level } h, \text{ close to level } (h+1)$$
$$c - 0.5 < \overline{H} \le c, \text{assigned to level } c$$

4.2. Application of real case to the calculation

In this paper, the studied set of comments was equal to {good, medium, poor}. According to the study of this paper's part 2, the evaluation level interval of the profile controlling and flooding potential evaluation indexes of the injection well of field D was determined; the standard value at all levels could be determined according to formula (3), shown in table 3. Water flooding development injection well D0760073 of filed D was used as the to-be-evaluated object u; the levels of the profile controlling and flooding feasibility of this well were ealuated using the variable fuzzy sets based comprehensive evaluation method. The evavluation indexes data of injection well D0760073 was shown in table 4.

Table 3. the evaluation levels of injection well's evaluation indexes

Evaluation level / Evaluation indexes	Intervals of evaluation levels			Graded standard value M_{ih}		
	Good	medium	poor	Good	medium	poor
variation coefficient	0.5∼0.7	> 0.7	< 0.5	0.6	0.7	0.5
Water absorption profile variation coefficient	> 0.6	0.5∼0.6	< 0.5	0.6	0.55	0.5
Permeability ($10^{-3}\mu m^2$)	$100 \sim 200$	> 300	< 100	200	300	100

Table 4. the profile feasibility evaluation data of injection well D0760073

Evaluation indexes	Permeability variation coefficient	Water absorption profile variation coefficient	Permeability ($\times 10^{-3}\mu m^2$)
Weight	0.42	0.28	0.3
Index value	0.57	0.59	235

The permeability variation coefficient of injection well D0760073 was $x_1 = 0.57$, falling into interval $[0.5, 0.6]$; therefore, according to formula (5), its relative membership degree to the level "poor" was calculated 0.3; according to formula (4), it was known that its relative membership degree to the level "good" was 0.7, and its relative membership degree to the level "medium" was 0. Thus, the relative membership degree vector of permeability variation coefficient was $r(x_1) = (0.7\ 0\ 0.3)$. With the same method, the relative membership degree vector of the water absorption profile variation coefficient was $r(x_2) = (0.8\ 0.2\ 0)$, and the relative membership degree vector of the permeability was $r(x_3) = (0.65\ 0.35\ 0)$.

With formula (6), the comprehensive relative membership degree of four groups of parameter combination was calculated respectively so as to constitute a comprehensive membership degree matrix, and its row vector was normalized to get the following matrix:

$$[v^0(u)]_{4\times 3} = \begin{bmatrix} 0.71 & 0.16 & 0.13 \\ 0.71 & 0.16 & 0.13 \\ 0.94 & 0.04 & 0.02 \\ 0.94 & 0.04 & 0.02 \end{bmatrix}.$$

According to formula (7), the level characteristic value was calculated respectively: $H_1 = 1.41$, $H_2 = 1.41$, $H_3 = 1.058$, and $H_4 = 1.08$; the mean value was calculated: $\overline{H} = 1.25$; in the end, the feasibility evaluation level of the injection well D0760073 was judged "good" with variable fuzzy criterion, representing this well was very suitably used as profile controlling and flooding injection well.

5. Conclusion

(1) The screening indexes of profile controlling and flooding injection well were determined through qualitative analysis, and their evaluation level limits were determined through indoor experiment; thus, the reliability of the injection well profile controlling and flooding feasibility level comprehensive evaluation was guaranteed, and this was superior to other profile controlling decision-making methods.

(2) The levels of the profile controlling and flooding feasibility were evaluated using the variable fuzzy sets based comprehensive evaluation method and by taking the water flooding development injection well of field $D$for example; the evaluation results indicated that the well was suitably used as a profile controlling and flooding injection well. This method could be used for evaluating other injection wells at field D; finally a decision basis could be provided for the implementation of profile controlling and flooding in the heterogeneous mid-low permeability reservoir of field D.

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