Establishment and Application of Flow Field Evaluation System after Early Polymer Injection in Thick Reservoir

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Abstract: ***In view of the problem that it is difficult to further improve the recovery rate of offshore thick reservoir after long-term polymer injection and water injection, the distribution of underground reservoir flow field is studied. Taking Bohai L oilfield as the research object, various indexes describing the reservoir flow field are selected, the flow field strength is calculated by analytic hierarchy process and fuzzy evaluation method, and the comprehensive evaluation system of flow field is established. The feasibility of the evaluation method is verified by the mechanism model. It is applied in Bohai S oilfield. The flow field distribution and potential tapping area are defined. The adjustment wells are added in the weak flow field area, and the profile control is strengthened in the strong flow field area to optimize the water injection measures. The daily oil increase is 300 m^3/d, the cumulative oil increase is 5 ×10^4 m^3, and the potential tapping effect is better.***

Keywords: Polymer injection oilfield; Thick reservoir; Flow field evaluation; Numerical simulation; Flow field adjustment.

1. INTRODUCTION

After long-term polymer injection and water injection in offshore thick reservoirs, due to the large differences in formation heterogeneity and reservoir physical properties in different regions, the heterogeneity is strong. At the same time, due to the influence of gravity, the injected water quickly breaks through to the bottom of the production well along the channel with high permeability, and there are obvious contradictions between layers and planes. Therefore, it is of great significance to study the distribution of flow field in underground reservoirs for the adjustment of optimization schemes such as improving oil recovery policy in the next step.

At present, due to the diversity of reservoir types, there are many methods for evaluating the flow field of reservoirs. Zhong Dakang et al. [7] thought that the porosity and permeability will increase after long-term water injection, and the rock composition maturity is high and the degree of diagenetic evolution is low. Long-term water injection is the main reason for the formation of large pores. The research results of Li Cungui and Lin Yubao et al. [8] show that the pore characteristics of the reservoir are obviously improved in the high water cut period, the throat radius tends to increase, the throat sorting becomes better, and the median pore throat radius increases. Wang et al. [9] used the fuzzy ISODATA clustering method to determine the level of large pores. Peng Shimi et al. [10] introduced the concept of large channel comprehensive index, combined with fuzzy comprehensive evaluation technology to quantitatively identify the distribution law of channeling channels. Feng et al. [11] coupled the reservoir permeability evolution model with the reservoir fluid seepage equation to obtain the formation and evolution of large pores in the formation. Yu Chenglin et al. [12] obtained four parameters such as the coefficient of variation of the well group from the perspective of geology and development, and applied the comprehensive discriminant parameter method to quantitatively identify the development area of the channeling channel. Yang Huanwen et al. [13] used the injection-production correlation method to identify the channeling channel. Chen Fuzhen proposed to quantitatively describe the reservoir flow field by three parameters: displacement ratio, fluid flow rate and water saturation [14]. Jiang Ruizhong selected pore radius, water multiple, water cut and fluid flow rate as the evaluation indexes of reservoir flow field [15]. Most studies focus on multi-layer sandstone water injection oilfield, but there is no relevant research on the evaluation of reservoir flow field with the characteristics of early polymer injection, layer thickness and high-speed development. Considering the characteristics of the oilfield, various indexes describing the flow field of the reservoir are screened, and the flow field strength is calculated by the analytic hierarchy process and the fuzzy evaluation method. The comprehensive evaluation system of the flow field is established to describe the strength of the underground flow field, which lays a foundation for the formulation of the subsequent oilfield development adjustment plan.

2. THE ESTABLISHMENT METHOD OF FLOW FIELD COMPREHENSIVE EVALUATION SYSTEM

2.1 Influencing Factors and Characterization of Flow Field

The factors affecting the reservoir flow field include static geological factors and dynamic development factors, among which static factors mainly include porosity, permeability, reservoir thickness and sedimentary microfacies. Dynamic factors include water multiple, water production rate, fluid flow rate, oil displacement efficiency and so on. The static factor describes the geological basis for the formation of dominant and non-dominant flow fields. It is the innate condition for the formation of the flow field and can indicate the potential of the flow field formation. The direct characterization of the reservoir flow field is the dynamic factor, and its value reflects the actual erosion intensity of the reservoir flow field. The flow field strength determined by the static index is called the static flow field strength, and the flow field strength determined by the dynamic index is called the dynamic flow field strength. The total flow field strength can be determined by the static flow field strength and the dynamic flow field strength.

2.2 Comprehensive Screening of Indicators

The comprehensive screening of indicators was screened by logical analysis. The steps of the logical analysis method are to first analyze the physical meaning of each index in the screening system, study the influence degree of the index on the reservoir flow field, and what indexes are involved in the whole influence process, so as to determine the logical relationship between the indexes.

2.2.1 Screening of static indicators

Through the analysis of mercury injection data and sealed coring wells, it can be seen that the two factors of porosity and permeability are the external performance factors of flow field formation, which play a decisive role in the formation of dominant channels, but the two indicators of porosity and permeability are related to the pore radius. Therefore, the pore radius can be directly used as the main static index affecting the flow field.

2.2.2 Screening of dynamic indicators

The dynamic factors of the reservoir flow field directly determine the evolution law of the flow field. Considering the characteristics of the reservoir, the logical analysis method is used to select the final evaluation index according to the logical relationship between the dynamic factors. Bohai S oilfield is a high-speed development with few wells. The initial oil production rate reaches 4%. The higher the flow rate, the easier the sand particles fall off. The larger the sand production, the easier it is to form high permeability bands, and then form dominant seepage channels, affecting the reservoir flow field. When selecting the flow field characterization index of Bohai L oilfield, the influence of fluid velocity is considered. At the same time, there is a correlation between the fluid velocity and the injection-production pressure difference of the well, and the latter can be eliminated. The injection-production ratio and water storage rate are related to the water content, and the injection-production ratio and water storage rate can be removed. The water flow rate refers to the volume of injected water accumulated in the unit pore volume, which is the main manifestation of the strength and heterogeneity of the flow field. It is selected as the dynamic index of the flow field evaluation. Finally, the flow rate, water content and water flow rate are selected as the dynamic indexes of the flow field evaluation.

2.3 Establishment of Comprehensive Evaluation System of Reservoir Flow Field

Firstly, the static flow field strength and dynamic flow field strength are determined by analytic hierarchy process and fuzzy mathematics comprehensive evaluation method, and then the static and dynamic flow field strength are normalized. Secondly, the weights of static flow field strength and dynamic flow field strength are obtained by analytic hierarchy process and fuzzy mathematics method, which are multiplied by their respective values and then added. Finally, the total flow field strength is obtained after normalization.

2.3.1 Calculation of static flow field strength

The research shows that the larger the porosity and permeability are, the smaller the seepage resistance of the fluid in the porous medium is, and the easier it is to form the dominant flow field. Therefore, the ascending trapezoid formula method is used to calculate its membership degree:

$$r = \frac{r(i)-r_{min}}{rmin_{max},i=1,2\ldots n} \tag{1}$$

The membership degree of n grids is obtained for the above porosity, and the membership matrix of static factors is obtained as follows:

$$R_j = (r_{11}, r_{21} \ldots r_{n1})^T \tag{2}$$

There is only one parameter in the static index. Therefore, the weight value of the pore throat radius is 1, and the static flow field strength can be calculated by multiplying it with the membership value. After normalization, the distribution of the static flow field strength can be obtained and represented by F_j.

2.3.2 Calculation of dynamic flow field intensity

The membership function of each index is determined by fuzzy mathematics.

1) Overwater multiples

It is defined as the volume of injected water accumulated in unit pore volume, which is a cumulative index according to the influence of flow field strength. The results show that there is a good linear relationship between the intensity of the flow field and the logarithm of the water-passing multiple. The membership function $f(Rw(i))$ of the water-passing multiple is determined by the ascending trapezoid method.

$$f\left(Rw(i)\right) = \frac{ln\,Rw(i)-ln\,Rw_{\min}}{ln\,Rw\;ln\,R_{\min_{max}}} \tag{4}$$

2) Water yield rate

Another characteristic of the formation of the dominant channel is the sudden change of water production rate. The viscosity of water is small, which is easy to cause fingering in uneven media and form dominant channels. The oilfield in the middle and late stages of development belongs to the high water cut stage, and the water production rate in some areas is as high as 98 %. Therefore, the water production rate is one of the key dynamic factors to study the formation of the dominant flow field. The membership function $f(Fw)$ of water production rate is determined by the ascending trapezoid method:

$$f(Fw) = \frac{Fw(i)-Fw_{min}}{Fwmin_{max}i=1,2\ldots n} \tag{5}$$

3) Fluid velocity

The fluid velocity is an instantaneous index. The greater the fluid velocity, the greater the instantaneous erosion degree of the fluid to the reservoir, and the greater the strength of the reservoir flow field. The membership function$f(Ql)$ of fluid velocity is determined by the ascending trapezoid method:

$$f\left(Ql(i)\right) = \frac{ln\,QL(i)-ln\,Ql_{min}}{ln\,Ql\;ln\,Q_{min_{max}}i=1,2\ldots n} \tag{6}$$

The membership degrees of the three indexes of water flow multiple, water production rate and fluid flow rate are obtained respectively. Each index has the membership degree of n grids, and the membership degree matrix is composed of:

$$R_d = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{n3} \end{pmatrix} \tag{7}$$

According to the analytic hierarchy process, the evaluation matrix of dynamic indicators is established, as shown in the following table.

Table 1: Evaluation matrix of dynamic characteristic parameters

dynamic factors	Overwater multiple	rate of curve of flow of fluid	water production rate
Overwater multiple	1	1/2	1/3
rate of curve of flow of fluid	2	1	1/2
water production rate	3	2	1

Through the analytic hierarchy process, the weight vector of water flow multiple, fluid flow rate and water content can be obtained as follows:

$$\omega_d = (0.1634,0.297,0.5396)^T \quad (8)$$

$$F_d = R_d \cdot \omega_d = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{n3} \end{pmatrix} \cdot (0.1634,0.297,0.5396)^T = (b_1, b_2 \dots b_n)^T \quad (9)$$

In the formula (7), R is multiplied by ω_d, that is, the formula (9), that is, the distribution of dynamic flow field intensity F_d.

The distribution of dynamic flow field intensity can be obtained by normalizing the above dynamic flow field intensity. The dynamic flow field intensity is expressed by Fs:

$$F_J = (b_1, b_2 \dots b_n)^T / max(b_1, b_2 \dots b_n) \quad (10)$$

2.3.3 Calculation of comprehensive flow field intensity

The final total flow field intensity of the reservoir is the result of the combined action of static factors (internal factors) and dynamic factors (external factors). Therefore, it is necessary to calculate the membership degree and weight value of the dynamic flow field strength and the static flow field strength respectively to determine the total flow field strength.

Similarly, the analytic hierarchy process is used to establish the judgment matrix of the total flow field strength. Since the static index is only one of the physical conditions for the formation of the dominant channel, the dynamic index is an important condition for the formation of the dominant channel. Therefore, the scale of the dynamic index is 2, indicating that the dynamic index is slightly more important than the static index. According to the analytic hierarchy process, the judgment matrix of the two indicators is established, and the weights of the two indicators are calculated, as shown in the following table:

Table 2: Static and dynamic index weight table

parameter	static index	dynamic indexes	weighted value
static index	1	0.5	0.33
dynamic indexes	2	1	0.67

The static flow field strength and dynamic flow field strength calculated above are multiplied by their weights respectively, and then the comprehensive flow field strength distribution of the reservoir is obtained by adding them.

Then the comprehensive flow field strength is

$$F_z = F_D \cdot \omega_D + F_J \cdot \omega_J \quad (11)$$

Table 3: Total flow field intensity grading statistical results

level	flow field	range
1	Absolute dominant flow field	>0.6
2	Advantage flow field	0.4～0.6
3	Non-dominant flow field	0.2～0.4
4	Absolutely non-dominant flow field	<0.2

The flow field strength evaluation system is applied to the actual block to study the flow field strength of the oilfield, and the flow field strength is classified to determine the location of the dominant flow field, and then the flow field is reformed to improve the recovery rate of the entire oilfield.

2.3.4 Verification of the results

According to the above calculation process, the quantitative evaluation of the comprehensive flow field strength can be obtained. By using Matlab programming software to read the data, the flow field intensity map of the whole reservoir can be made. According to the development characteristics of Bohai S oilfield: less well high yield, early polymer injection, water flooding at the bottom of thick oil layer and high speed development at sea, the conceptual models are designed by Eclipse software to verify the feasibility of the flow field strength evaluation method.

2.3.4.1 Plane verification

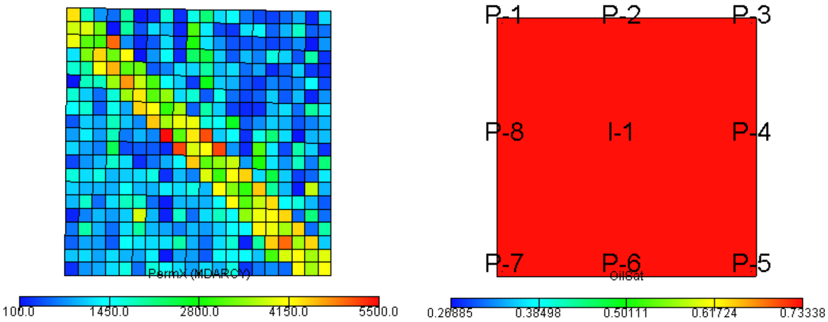
1) Establishment of the model

a) Grid setting: the number of grids is 20 × 20 × 3, the length is 50 × 50 × 10m, and the longitudinal direction is 1 layer. The porosity is about 0.3, and the permeability is 300mD ~ 4000mD.

b) Well pattern setting: According to the early well pattern arrangement of Lvda 10-1 oilfield, the inverted nine-spot well pattern is set up, and the well spacing is 500 m. The well arrangement is shown in the following figure.

c) Working system: According to the annual average injection-production ratio, the injection-production ratio of the model is set to 0.91; the production cycle is 800 days.

d) The water flooding scheme is continuous water flooding for 800 days, and the early polymer injection scheme is to carry out polymer flooding for 300 days first and then water flooding for 500 days.

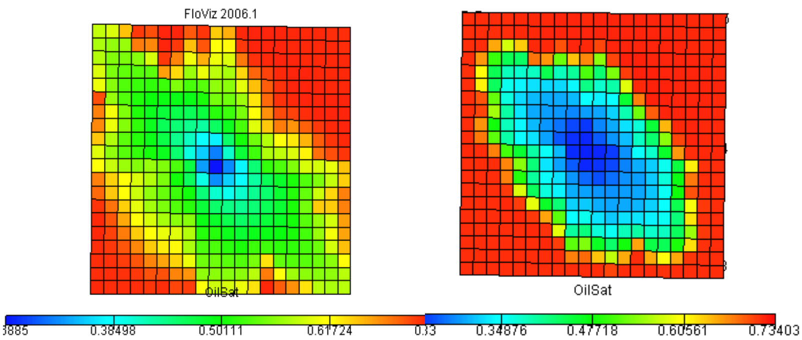


(a) Permeability distribution map (b) Development well location distribution

Figure 1: Plane permeability distribution and development well pattern distribution map

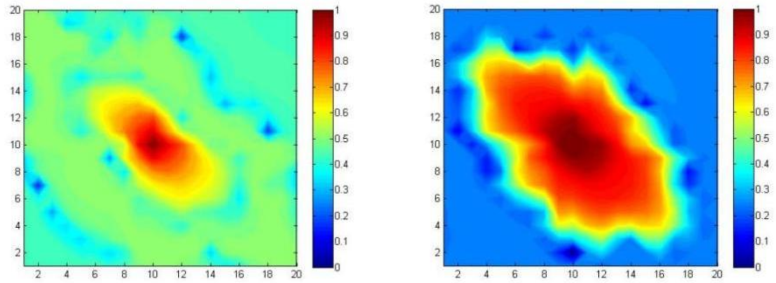
2) Analysis of simulation results

After the development of water injection and early polymer injection respectively, the two models form oil saturation diagram and water multiple diagram. The flow field intensity diagram and flow field classification diagram are formed by using the method in this paper. The results are as follows:



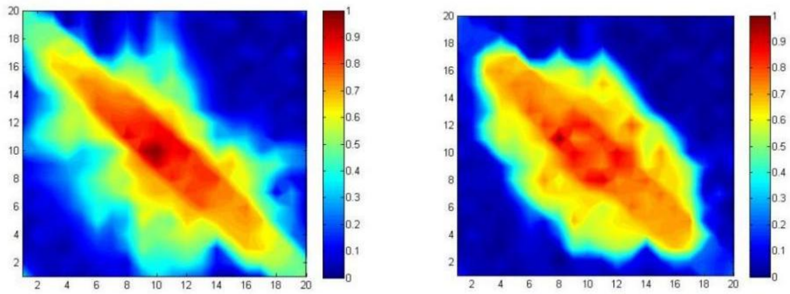
(a) water injection development (b) early polymer injection development

Figure 2: Oil saturation diagram under different development methods



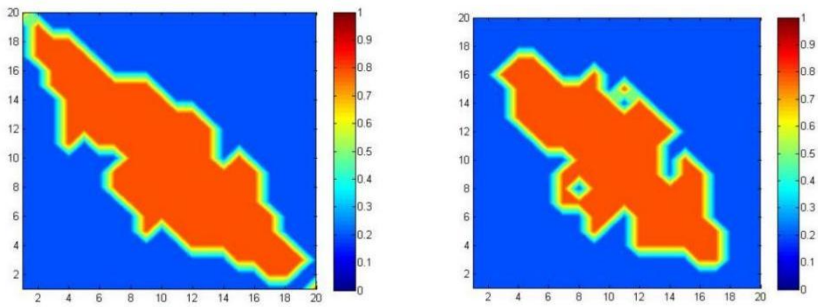
(a) water injection development (b) early polymer injection development

Figure 3: Overwater multiples under different development methods



(a) water injection development (b) early polymer injection development

Figure 4: Flow field intensity diagram under different development methods



(a) water injection development (b) early polymer injection development

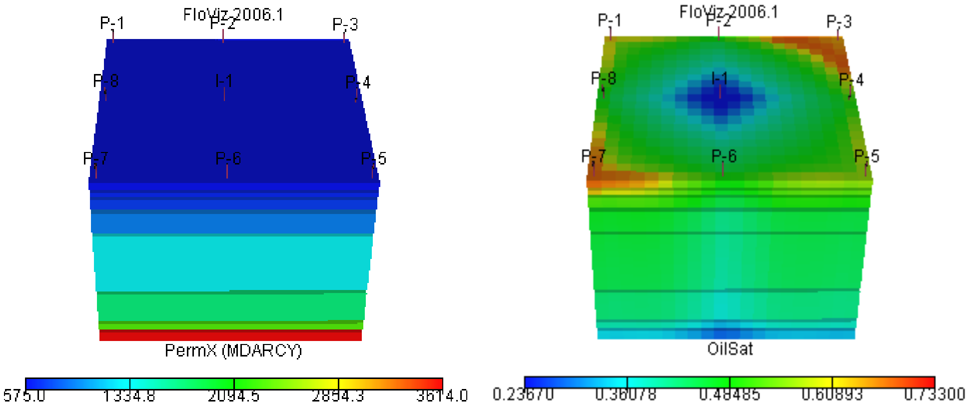
Figure 5: Flow field intensity classification diagram under different development methods

It can be seen that compared with water flooding development, early polymer injection development has low diffusion speed and small sweep range in high permeability area due to polymer plugging high permeability channel, but the displacement effect is good (Figure 2); in the early stage of polymer injection development, the flow field intensity map (Figure 3) reflecting the effect of high permeability channel is better than the remaining oil saturation map (Figure 2) and the water multiple map (Figure 3). The classification of flow field diagram is more obvious (Figure 5), which is more meaningful for the hierarchical management of high permeability area. The intensity of the flow field is graded. When the flow field intensity is greater than 0.5, there is connectivity between the production well and the water injection well, and the high permeability strip can be identified.

2.3.4.2 Vertical verification

1) Establishment of model

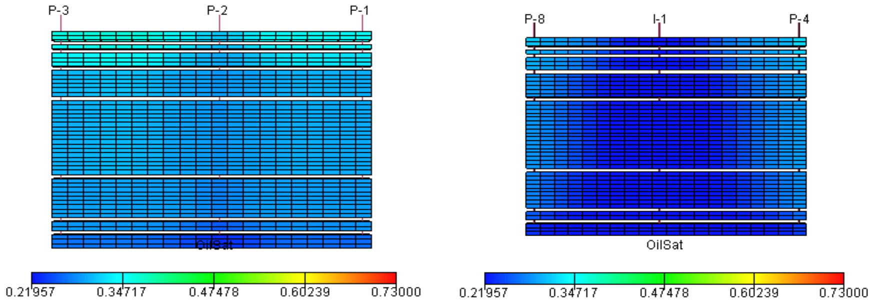
The number of grids is 20 × 20 × 50, the length is 50 × 50 × 1.5m, and the thickness is 65 m. The porosity is about 0.3, the thick reservoir is positive rhythm reservoir, and the permeability is 300mD ~ 4000mD. Inverted nine-point well pattern, injection-production ratio is 0.91; the production cycle is 1000 days. The oil saturation of the reservoir at the initial time is about 50% by setting the water flooding model at the bottom of the thick oil layer.



(a) permeability distribution map (b) initial oil saturation map

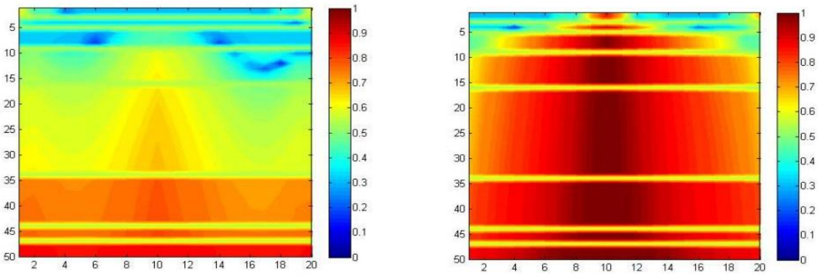
Figure 6: Longitudinal permeability distribution and initial oil saturation diagram

After a period of water flooding and early polymer injection, the longitudinal sections of the model i = 1 and i = 10 were intercepted for comparative analysis.



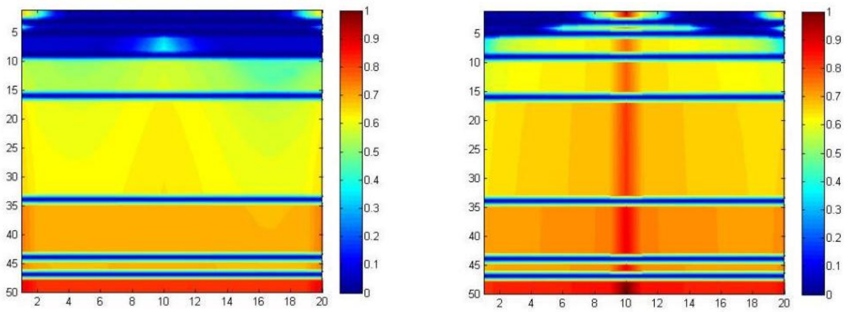
(a) oil saturation diagram (i = 1) (b) oil saturation diagram (i = 10)

Figure 7: Oil saturation diagram



(a) water multiple figure (i = 1) (b) water multiple figure (i = 10)

Figure 8: Water multiples



(a) flow field intensity diagram (i = 1) (b) flow field intensity diagram (i = 10)

Figure 9: Flow field intensity diagram

It can be seen that the remaining oil saturation map (Figure 7) and the water multiple (Figure 9) of the thick oil reservoir model cannot identify the reservoir characteristics; the greater the intensity of the flow field (Figure 9), the better the connectivity of the reservoir, the stronger the flow capacity, the greater the possibility of the existence of high permeability channels, and the more obvious the flow field classification of thick reservoirs. The flow field intensity evaluation diagram can identify the position of the high permeability channel to a certain extent.

3. FIELD APPLICATION EFFECT ANALYSIS

3.1 Establishment of Flow Field Evaluation System in Block

According to the above calculation process, the quantitative evaluation of the comprehensive flow field strength can be obtained. Using Matlab programming software to read the data, the flow field intensity diagram of the whole reservoir can be made (Figure 10).

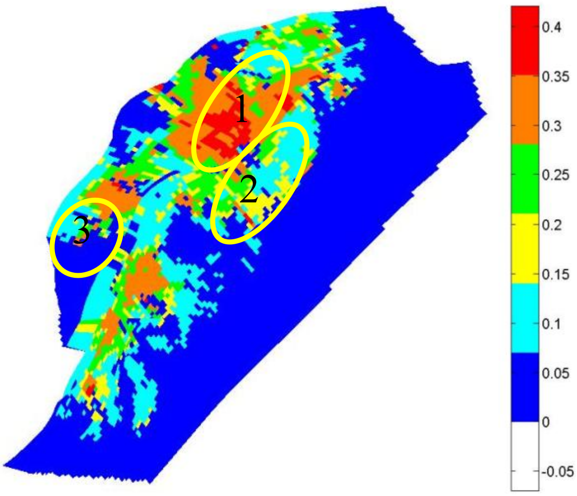


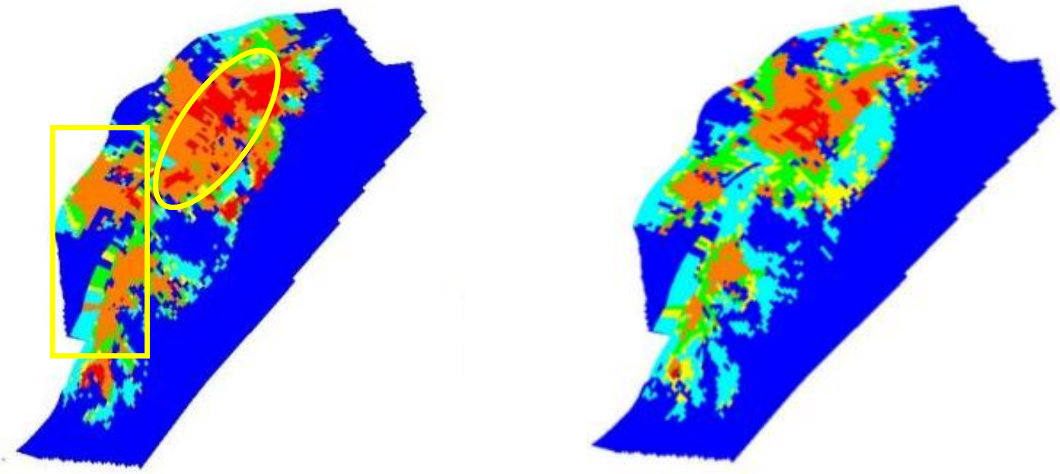
Figure 10: II-2 small layer flow field intensity diagram

3.2 Readjustment of the flow field in the block

According to the distribution of the flow field, the flow field is re-adjusted. In the main mining area, the 1 area with high flow field intensity has been fully displaced, while the 2 and 3 areas with rich remaining oil have a low degree of spread, and the plane contradiction is prominent. It is necessary to adjust the well pattern to change the streamline of the 2 area to displace the enriched remaining oil, increase new oil wells and transfer some oil wells with high water content, so as to improve the streamline.

With the guiding ideology of optimizing seepage field, improving injection-production system and enhancing oil recovery, a hydrodynamic potential tapping scheme to improve plane contradiction and interlayer contradiction is formulated. In view of the plane contradiction, the well network reorganization, oil well liquid extraction, injection production structure adjustment and other schemes are carried out. In view of the vertical contradiction, the layered fine water injection scheme is carried out, and the scheme prediction is carried out by numerical simulation. Finally, 8 wells were converted to 8 wells, 8 new wells were added, and the original inverted nine-spot well pattern was converted to a row well pattern. The methodology was ultimately applied to Bohai L Oilfield. In areas with weaker flow fields, eight additional adjustment wells were drilled, while in regions with stronger flow fields, profile control measures and optimized water injection strategies were enhanced. These measures resulted in a daily oil production increase of 300 m^3/d and a cumulative incremental production of 5×10^4 m^3, demonstrating favorable potential tapping outcomes.

Before and after the flow field adjustment, as shown in Figure 4, it can be seen that after the adjustment, the previous strong dominant flow field area is reduced, the weak dominant flow field and the non-dominant flow field part area evolve into the dominant flow field, and the non-uniformity of the flow field distribution is improved (Figure 11), which improves the economic benefits of the entire oilfield.



(a) before adjustment (b) after adjustment

Figure 11: Flow field intensity change and mining effect diagram after well pattern reorganization and development

4. CONCLUSION

l) The multi-parameter comprehensive evaluation method is used to characterize the flow field intensity. Compared with the displacement multiple, it can more reasonably reflect the flow field of early polymer injection, thick layer, few wells, high yield and high-speed development reservoirs.

2) Using the logic analysis method to screen the evaluation index of the flow field, the flow field is classified, and finally a set of perfect reservoir flow field evaluation system is established.

3) The reservoir flow field evaluation system is applied to the field block to clarify the potential tapping area in the later stage. Different flow field adjustment schemes are designed and the best scheme is optimized. After adjustment, the inhomogeneity of flow field distribution is improved, and the purpose of enhancing oil recovery is achieved.

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