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Optimization Method for Fine Water Injection in the High Water-Cut Stage of Multi-Layer Heterogeneous Heavy Oil Reservoirs

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Abstract

Aiming at the problem of uneven planar and vertical water flooding in offshore multi-layer reservoirs, this paper establishes a fine water injection optimization method based on injection-production connectivity by using reservoir engineering and numerical simulation methods. According to the equivalent seepage resistance method, a water-drive model for multi-layer reservoirs is established, and the planar connectivity coefficient is calculated through this model. The injection-production connectivity value is further calculated from the connectivity coefficient. Based on the goal of vertical and planar balanced displacement, the formulas for adjusting layered water injection rate and planar liquid production rate are derived. The research results show that the calculation method of the connectivity coefficient is fast, and the difference with the numerical simulation results is small; the fine water injection optimization method based on connectivity can better alleviate the interlayer and planar contradictions, and the well group recovery factor can be increased by more than 2%. The research results can effectively guide water-drive reservoirs to achieve three-dimensional balanced displacement and improve development effects.

Keywords

Water-Drive Development, Multi-Layer Reservoir, Connectivity Coefficient, Injection-Production Connectivity Value, Balanced Displacement, Production and Injection Allocation

1. Introduction

Bohai B Oilfield is a multi-layer heterogeneous reservoir, developed by water injection with an irregular areal well pattern and a single development layer series in the vertical direction. At present, the oilfield has entered the ultra-high water cut period, with prominent planar contradictions in local areas and vertical interlayer contradictions (Zhou, 2009; Zhou, 2007; Han, 2007; Hu, 2007). At home and abroad, scholars have conducted extensive research on water injection optimization methods for multi-layer reservoirs. Cui Chuanzhi et al. studied the layered injection allocation method aiming at vertical balanced displacement (Cui et al., 2012; Cui et al., 2017; Ma et al., 2019; Sun et al., 2018; Jia et al., 2012; Chen et al., 2019); Yan Ke, Feng Qihong et al. studied the balanced water-drive adjustment method for planar heterogeneous reservoirs (Yan et al., 2015; Feng et al., 2016; Chang et al., 2019; Wang et al., 2011; Cui et al., 2016; Han et al., 2017; Yang et al., 2019). These methods mainly solve the problem of uneven vertical or planar water flooding unilaterally, and it is difficult to comprehensively alleviate vertical and planar contradictions; most of them are unable to provide quantitative guidance for injection-production adjustment. To address the above problems, in order to alleviate the vertical and planar contradictions of offshore multi-layer reservoirs, a calculation method of the connectivity coefficient is established based on the equivalent seepage resistance method. The water-drive volume of injection wells in different directions of each oil layer is clarified by calculating the connectivity coefficient. The injection-production connectivity values in different water-drive directions are further calculated according to the connectivity coefficient. With the goal of balanced displacement, a fine water injection optimization method based on the idea of balancing vertical and planar injection-production connectivity values is established. For well groups with uneven water flooding, it guides the layered injection allocation of injection wells and the adjustment of planar liquid production structure, so that the injected water can achieve balanced displacement in both plane and vertical directions, and improve the overall water-drive development effect of the well group.

2. Calculation Method of the Connectivity Coefficient

2.1. Assumptions

A mathematical model is established for multi-layer heterogeneous reservoirs with the following basic assumptions:

1) Non-piston-like water displacement of oil, with an oil-water two-phase zone.
2) Rigid porous medium, and incompressible fluids.
3) Stable interlayer barriers exist, and interlayer cross-flow is not considered.
4) Injection-production balance is maintained within the well group.

2.2. Division of Injection-Production Units

For multi-layer commingled production reservoirs, the injection-production unit refers to the seepage area controlled between injection and production wells in each oil layer, which is mainly affected by the injection-production well pattern and planar heterogeneity. Based on streamline numerical simulation, it is found that the angle of the injection-production unit is basically consistent with the angle between the bisectors of the connecting lines of two adjacent groups of injection-production wells (Feng et al., 2014; Chen et al., 2018).

2.3. Calculation of Connectivity Coefficient

Based on the equivalent seepage resistance method, the seepage resistance in each injection-production unit is (Zhang et al., 2006):

$$R_{i,j,k}=\begin{cases}\dfrac{1}{K_{i,j,k}h_{i,j,k}\theta_{i,j,k}}\cdot\left(\displaystyle\int_{r_{\mathrm{w}}}^{r_{\mathrm{fi},j,k}}\frac{1}{\left(\dfrac{K_{\mathrm{ro}}}{\mu_{\mathrm{o}}}+\dfrac{K_{\mathrm{rw}}}{\mu_{\mathrm{w}}}\right)r}\mathrm{d}r+\mu_{\mathrm{o}}\cdot\ln\frac{r_{i,j,k}}{r_{\mathrm{fi},j,k}}+\mu_{\mathrm{o}}\cdot\frac{\theta_{i,j,k}}{2\pi}\cdot\ln\frac{r_{i,j,k}\theta_{i,j,k}}{2\pi r_{\mathrm{w}}}\right) & r_{\mathrm{fi},j,k}<r_{i,j,k}\\[3ex] \dfrac{1}{K_{i,j,k}h_{i,j,k}\theta_{i,j,k}}\cdot\left(\displaystyle\int_{r_{\mathrm{w}}}^{r_{i,j,k}}\frac{1}{\left(\dfrac{K_{\mathrm{ro}}}{\mu_{\mathrm{o}}}+\dfrac{K_{\mathrm{rw}}}{\mu_{\mathrm{w}}}\right)r}\mathrm{d}r+\frac{1}{\dfrac{K_{\mathrm{ro}}(S_{\mathrm{we}})}{\mu_{\mathrm{o}}}+\dfrac{K_{\mathrm{rw}}(S_{\mathrm{we}})}{\mu_{\mathrm{w}}}}\cdot\frac{\theta_{i,j,k}}{2\pi}\cdot\ln\frac{r_{i,j,k}\theta_{i,j,k}}{2\pi r_{\mathrm{w}}}\right) & r_{\mathrm{fi},j,k}>r_{i,j,k}\end{cases}\tag{1}$$

In the formula, $R_{i,j,k}$ is the seepage resistance of the injection-production unit where the i-th production well and the j-th injection well are located in the k-th small layer, mPa·s/(μm²·mm); $K_{i,j,k}$ is the average permeability in the injection-production unit, 10^{-3} μm²; $h_{i,j,k}$ is the average oil layer thickness in the injection-production unit, m; $\theta_{i,j,k}$ is the angle of the injection-production unit; $r_{\mathrm{f}i,j,k}$ is the position of the water-drive front in the injection-production unit, m; $r_{i,j,k}$ is the equivalent radius of the injection-production unit, m.

Among them, the equivalent radius of the injection-production unit can be calculated according to the area of the injection-production unit (Li et al., 2018):

$$r_{i,j,k}=\sqrt{\frac{2S_{\mathrm{A}i,j,k}}{\theta_{i,j,k}}}\tag{2}$$

In the formula, $S_{\mathrm{A}i,j,k}$ is the area of the injection-production unit, m².

It is assumed that there are oil layers in the multi-layer reservoir vertically, and any production well corresponds to an injection well, and any injection well corresponds to a production well.

Then, the formula for single-well liquid production is obtained from simultaneous equations with the production well as the center:

$$\sum_{k=1}^{N_{\mathrm{L}}}\sum_{j=1}^{N_{\mathrm{w}}}\frac{p_j(t)-p_i(t)}{R_{i,j,k}(t)}=q_{\mathrm{L}}(t)\tag{3}$$

In the formula, $p_i(t)$ is the bottom hole pressure of a production well at time t, MPa; $p_j(t)$ is the bottom hole pressure of the corresponding injection well of a production well at time t, MPa; $q_{\mathrm{L}}(t)$ is the liquid production rate of a production well at time t, m³/d.

The formula for the single well water injection rate is obtained by simultaneous equations with the injection well as the center:

$$\sum_{k=1}^{N_{\mathrm{L}}}\sum_{i=1}^{N_{\mathrm{o}}}\frac{p_j(t)-p_i(t)}{R_{i,j,k}(t)}=q_{\mathrm{I}}(t)\tag{4}$$

In the formula, $q_I(t)$ is the water injection rate of an injection well at time t, m^3/d.

Considering the injection-production balance, the average formation pressure remains stable:

$$\sum_{i=1}^{n} P_i(t) \Big/ n = \overline{p}_e \tag{5}$$

In the formula, P_i is the formation pressure in the injection-production unit, MPa; $\overline{p}_e$ is the average formation pressure, MPa.

The formation pressure in the injection-production unit can be approximately obtained by averaging the bottom-hole pressures of production wells and injection wells in the unit.

The bottom hole pressures of injection wells and production wells at time t are obtained by solving Equations (3) - (5) simultaneously.

At this time, the flow rate of the injection-production unit where the i-th production well and the corresponding j-th injection well are located in the k-th small layer is:

$$Q_{i,j,k}(t) = \frac{p_j(t) - p_i(t)}{R_{i,j,k}(t)} \tag{6}$$

In the formula, $Q_{i,j,k}$ is the flow rate of the injection-production unit where the i-th production well and the j-th injection well are located in the k-th small layer, m^3/d.

According to the principle of material balance, the oil-water front equation in the injection-production unit derived from the flow rate in the unit is satisfied by:

$$r_{\mathrm{fi},j,k}^2 = \frac{2\int_0^t Q_{i,j,k}\,\mathrm{d}t}{\phi_{i,j,k} h_{i,j,k} \theta_{i,j,k}} f_{\mathrm{w}}'(S_{\mathrm{w}}) + r_{\mathrm{w}}^2 \tag{7}$$

In the formula, S_w is the water saturation; $f_{\mathrm{w}}'(S_{\mathrm{w}})$ is the derivative of water cut.

The connectivity coefficient is defined as the distribution ratio of injection wells in different injection-production directions. The inter-well connectivity coefficient can be calculated from the flow rate in the injection-production unit:

$$\alpha_{i,j,k} = \frac{Q_{i,j,k}(t)}{\sum_{i=1}^{N_{\mathrm{o}}} Q_{i,j,k}(t)} \tag{8}$$

The heterogeneity of the reservoir causes the displacement of injected water to be uneven in all directions, and the corresponding seepage resistance in the injection-production unit varies. In actual calculations, a certain time step should be selected for iterative calculation (as shown in Figure 1).

3. Fine Water Injection Optimization Method

To characterize the displacement degree of injected water in each water-drive direction, the concept of injection-production connectivity value is introduced. The injection-production connectivity value is the ratio of the cumulative water passing through between injection and production wells to the geological reserves, that is, the cumulative water passing through per unit geological reserve. Through reservoir engineering derivation (Sun et al., 2020), the injection-production connectivity value and the inter-well oil saturation satisfy.

$$\lambda = \frac{\mu_o B_o}{\mu_w B_w \left(1 - S_{wc}\right) dc} e^{cS_{wc}} \cdot \left[e^{c\left(S_{oi} - S_o\right)} - 1 \right] + \frac{S_{oi} - S_o}{S_{oi}} \tag{9}$$

In Equation (9), c and d satisfy:

$$\frac{K_{ro}}{K_{rw}} = de^{-cS_w} \tag{10}$$

In the formula, K_{ro} is the oil-phase relative permeability; K_{rw} is the water-phase relative permeability; c and d are constants related to reservoir and fluid properties, it can be obtained through laboratory core displacement experiments; B_o is the formation oil volume factor; B_w is the formation water volume factor; S_{wc} is the irreducible water saturation between injection and production wells; S_{oi} is the original oil saturation; S_o is the current average oil saturation between injection and production wells.

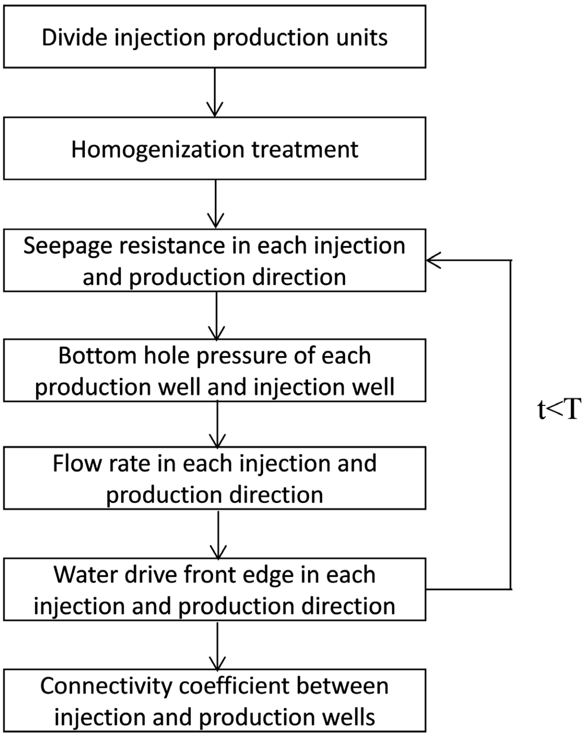


Figure 1. Program flowchart for connectivity coefficient calculation.

It can be seen from formula (9) that the larger the injection-production connectivity value, the smaller the inter-well oil saturation and the better the displacement effect; conversely, the smaller the injection-production connectivity value, the worse the displacement effect. Based on the goal of balanced displacement, for multi-layer commingled production reservoirs, it is necessary to optimize the layered injection allocation vertically and adjust the planar liquid production structure, so that the injection-production connectivity values between different oil layers and between different water-drive directions of the same oil layer tend to be consistent.

According to the divided injection-production units and the calculated connectivity coefficients, the injection-production connectivity values of any injection well in different injection-production directions (i.e., different injection-production units) of each oil layer can be obtained.

$$\lambda_{i,j} = \frac{Q_{i,j}}{N_{i,j}} = \frac{Q_i \cdot \alpha_{i,j}}{S_{\mathrm{A}i,j} \cdot \overline{h}_{i,j} \cdot \overline{\phi}_{i,j} \cdot S_{\mathrm{oi}}} \tag{11}$$

In the formula: $\lambda_{i,j}$ is the injection-production connectivity value of any injection well in the j-th injection-production unit of the i-th small layer; $Q_{i,j}$ is the cumulative water injection in the j-th injection-production unit of the i-th small layer, m^3; $N_{i,j}$ is the geological reserve of the j-th injection-production unit of the i-th small layer, m^3; Q_i is the cumulative water injection in the i-th small layer, m^3; $\alpha_{i,j}$ is the connectivity coefficient of the j-th injection-production unit of the i-th small layer; $S_{\mathrm{A}i,j}$ is the area of the j-th injection-production unit of the i-th small layer, m^2; $h_{i,j}$ is the average oil layer thickness of the j-th injection-production unit of the i-th small layer, m; $\phi_{i,j}$ is the average porosity of the j-th injection-production unit of the i-th small layer.

Based on the idea of balanced displacement, optimization and adjustment are carried out. After adjustment, balanced displacement is achieved in all injection-production directions, and the injection-production connectivity values between all injection and production wells tend to be consistent, that is:

$$\lambda_{i,j} + \Delta\lambda_{i,j} = \overline{\lambda} \tag{12}$$

$$\frac{Q_{i,j}}{N_{i,j}} + \frac{q_{\mathrm{I}i,j}\Delta t}{N_{i,j}} = \overline{\lambda} \tag{13}$$

In the formula, $\Delta\lambda_{i,j}$ is the variation of the injection-production connectivity value of the j-th injection-production unit of the i-th small layer of the injection well; Δt is the regulation time, d; $q_{\mathrm{I}i,j}$ is the daily water injection rate of the j-th injection-production unit of the i-th small layer, m^3/d.

The geological reserves, daily water injection rate, and cumulative water injection of each oil layer of the injection well satisfy:

$$N = \sum_{i=1}^{n} N_i = \sum_{i=1}^{n}\sum_{j=1}^{m} N_{i,j} \tag{14}$$

$$q_{\mathrm{I}} = \sum_{i=1}^{n} q_{\mathrm{I}i} = \sum_{i=1}^{n}\sum_{j=1}^{m} q_{\mathrm{I}i,j} \tag{15}$$

$$Q = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n}\sum_{j=1}^{m} Q_{i,j} \tag{16}$$

In the formula, N is the total geological reserve of the injection well in each oil layer, m^3; N_i is the geological reserve of the injection well in the i-th small layer, m^3; q_{I} is the daily water injection rate of the injection well, m^3/d; $q_{\mathrm{I}i}$ is the daily water injection rate of the i-th small layer, m^3/d; Q is the cumulative water injection of the injection well, m^3; Q_i is the cumulative water injection of the i-th small layer, m^3.

The optimized injection allocation of the injection well in each small layer can be obtained by solving Equations (12) - (16) simultaneously:

$$q_{\mathrm{I}i}=\frac{N_i}{N}\left(q+\frac{Q}{\Delta t}\right)-\frac{Q_i}{\Delta t} \tag{17}$$

The adjustment formula for the liquid production rate of each production well is obtained based on the layered injection allocation and the inter-well connectivity coefficient:

$$q_{\mathrm{L}}=\sum_{i=1}^{n}\left[\frac{N_{i,j}}{N_i}\left(q_i+\frac{Q_i}{\Delta t}\right)-\frac{Q_i\cdot\alpha_{i,j}}{\Delta t}\right] \tag{18}$$

Compared with the conventional layered water allocation method, the new method comprehensively considers geological factors and production performance factors, featuring simpler parameter acquisition, convenient and fast calculation, and strong applicability.

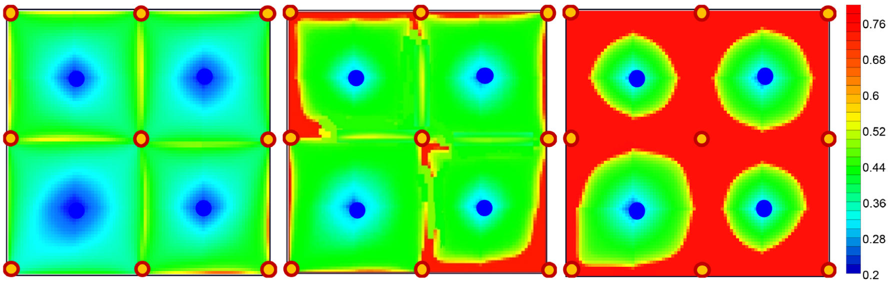
4. Case Application

4.1. Application of the Conceptual Model

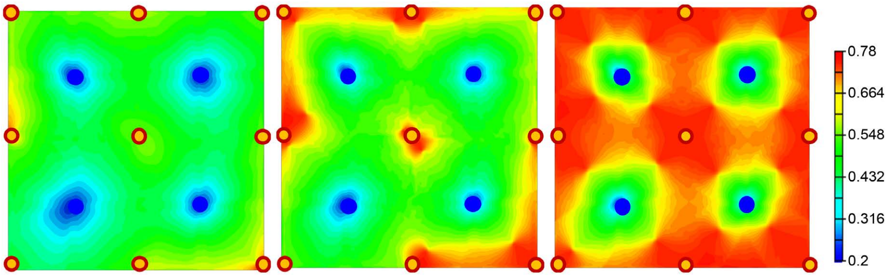
Taking a block of Bohai B Oilfield as an example, a multi-layer reservoir model is established based on the actual geological and reservoir parameters of the oilfield. The model considers 4 injection-production well groups with a five-spot well pattern, including 4 injection wells and 9 production wells. In the model, production wells produce at a fixed liquid rate to maintain injection-production balance; the injection-production well spacing is 300 m, the reservoir width is 200 m, the thickness of each small layer is 15 m vertically, the porosity is 0.3, the oil phase viscosity under reservoir conditions is 30 mPa·s, the water phase viscosity is 0.7 mPa·s, the residual oil saturation is 0.2, and the irreducible water saturation is 0.25; there are 3 small layers vertically with permeabilities of 3000×10^{-3} μm^2, 1500×10^{-3} μm^2 and 500×10^{-3} μm^2, respectively. Using the above model, the water-drive dynamics of each oil layer are simulated. At the same time, according to the above model conditions, a multi-layer reservoir numerical model is established with the same parameters as the reservoir model, and the simulation results of the two methods are compared (the simulation parameters are shown in **Table 1**). It is found that under the same displacement time, the water-drive front positions and saturation field distributions of different oil layers calculated by the two models are basically the same (as shown in **Figure 2**), which confirms that the calculation results of this model are basically consistent with the numerical simulation results and also illustrates the reliability of the model calculation.

Table 1. Liquid volume parameters of production wells and injection wells.

Well Name	Liquid Rate ($m^3 \cdot d^{-1}$)	Well Name	Liquid Rate ($m^3 \cdot d^{-1}$)
P1	50	P8	150
P2	100	P9	30
P3	80	I1	200
P4	100	I2	300
P5	320	I3	500
P6	170	I4	200
P7	200		



Reservoir Numerical Simulation (10a)



Multi-Layer Reservoir Model (10a)

Figure 2. Water drive front positions and saturation distributions of each layer.

The fine water injection optimization method is verified on the basis of the numerical model. The data from the numerical simulation model running to the 5th year are selected as the initial data before optimization. Considering that the water cut of the reservoir model will be close to the ultimate water cut of 98% after 10 years, taking the regulation time of 10 years as an example, numerical simulation is used for verification, and mining is carried out in the following two cases: the basic scheme is to continue production with the original water injection rate and liquid production rate; the optimization scheme is to produce with the adjusted water injection rate and liquid production rate calculated according to the above method. Numerical simulation shows that after the regulation time, the recovery degrees of each oil layer vertically and each injection-production direction in the plane are the same, indicating that balanced displacement is achieved in each oil layer after fine water injection optimization (as shown in **Figure 3**), and the well group recovery factor is increased by 3.5%. As the regulation period shortens, the ultimate incremental oil recovery of the reservoir also decreases accordingly.

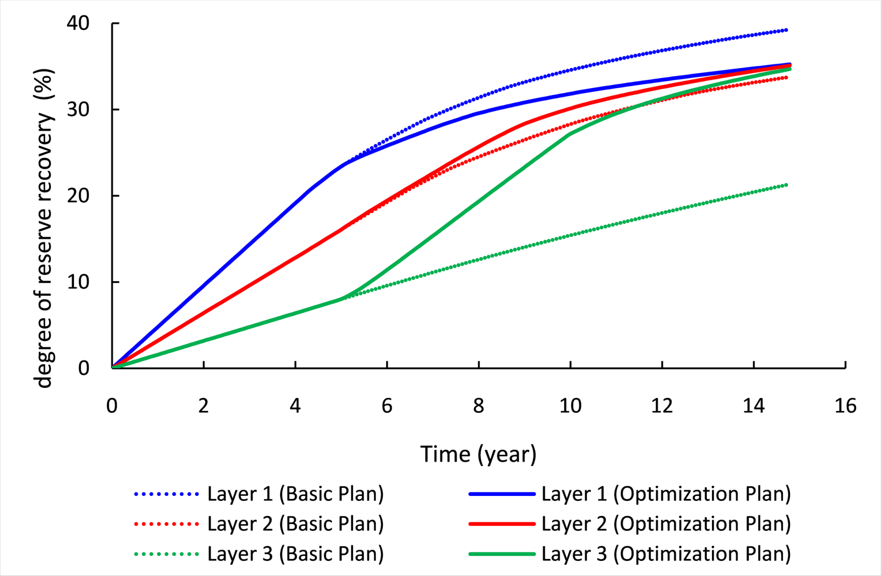


Figure 3. Recovery degrees of each vertical small layer.

4.2. Practical Application in the Reservoir

Bohai B Oilfield has entered the high water cut period, and the problem of uneven planar and vertical water flooding in well groups has become increasingly prominent. Using the method proposed in this paper, the layered injection allocation and liquid production rate of production wells are optimized for some well groups in the B Oilfield. Taking the F13 well group as an example, which mainly produces from the IV5 and IV8 layers, the injection-production connectivity values of each layer are calculated, and it is clarified that the main layer IV8 has a better water-drive effect, while the IV5 layer has a relatively poor water-drive effect. By increasing water injection into the IV5 layer in a targeted manner, the daily oil increase of the well group is 30 m^3, the water cut is reduced by 4%, and the well group recovery factor is increased by 2.1%. Taking the F26 well group as an example, which mainly produces from the IV3 and IV8 layers, the inter-well injection-production connectivity values of each layer are calculated, and it is clarified that the injected water of Well F26 in the IV3 layer is mainly driven to Well F27, and the injection-production connectivity value between Well F26 and Well F25 is small, with remaining oil. By shutting down the IV3 layer of Well F27, the water-drive direction of injected water is changed, the oil production of Well F25 is doubled, the daily oil increase is 26 m^3, the water cut is reduced by about 6%, and the well group recovery factor is increased by 2.3% (as shown in **Table 2**).

The research results have been applied to the entire oilfield, guiding 16 well groups in B Oilfield to adjust their liquid production rates, with an average daily oil increase of 30 m^3 per well group, achieving good development effects.

Table 2. Well group production rate and water cut.

Well Group Name	Before optimizing the water injection rate and liquid production rate		After optimizing the water injection rate and liquid production rate	
	Oil Rate ($m^3 \cdot d^{-1}$)	Water Cut (%)	Oil Rate ($m^3 \cdot d^{-1}$)	Water Cut (%)
F13	41	85	71	81
F26	54	92	80	86

5. Conclusions and Insights

1) A water-drive model for multi-layer reservoirs is established based on the equivalent seepage resistance method, and the connectivity coefficients of injection wells in different water-drive directions of each oil layer are calculated through this model. At present, the model does not consider the influence of factors such as edge-bottom water energy and gas cap on water flooding performance.

2) A fine water injection optimization method based on the idea of balancing injection-production connectivity values is established with the goal of achieving vertical and planar balanced displacement, which can effectively inhibit the channeling of injected water, reduce the ineffective water cycle of injected water, and achieve water cut reduction and oil increase.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Chang, H. J., Sun, G. Y., Chen, X. M., Zhai, S. Q., & Zhang, Y. H. (2019). Study and Application of Plane Injection-Production Optimization Based on Balanced Displacement. *Special Oil & Gas Reservoirs, 26,* 120-124.

Chen, C. L., Wang, X., Liu, X. et al. (2019). A Balanced Displacement Method for Waterflooding Multi-Layer Reservoirs Based on Maximum Net Present Value. *Special Oil & Gas Reservoirs, 26,* 123-125.

Chen, H. W., Feng, Q. H., Zhang, X. M., Wu, T. C., Zhou, W. S., & Liu, C. (2018). A Prediction Method for Waterflood Development Indicators of Multi-Layer Heterogeneous Reservoirs. *Fault-Block Oil & Gas Field, 25,* 473-476.

Cui, C. Z., An, R., Li, K. K. et al. (2016). Study on Optimization of Injection-Production Pressure Difference for Waterflooding in Low-Permeability Reservoirs. *Special Oil & Gas Reservoirs, 23,* 83-85.

Cui, C. Z., Jiang, H., Duan, J. H. et al. (2012). A Reasonable Zonal Injection Allocation Method for Separate-Layer Water Injection Wells Based on Interlayer Balanced Displacement. *Petroleum Geology and Recovery Efficiency, 19,* 94-96.

Cui, C. Z., Liu, L. J., Feng, Y. et al. (2017). Interval Division and Reasonable Injection Allocation Method for Staged Water Injection Based on Balanced Displacement. *Petroleum Geology and Recovery Efficiency, 24,* 67-71.

Feng, Q. H., Wang, X., Wang, B., Wang, D. P., & Wang, Y. Z. (2014). A Prediction Method for Development Indicators of Heterogeneous Waterflood Reservoirs. *Petroleum Geology and Recovery Efficiency, 21,* 36-39+113.

Feng, Q. H., Wang, X., Wang, D. P., & Huang, Y. S. (2016). Demonstration of Development Effect of Balanced Displacement in Waterflood Reservoirs. *Petroleum Geology and Recovery Efficiency, 23,* 83-88.

Han, D. K. (2007). Study on Accurately Predicting Relatively Enriched Areas of Remaining Oil to Improve Waterflood Recovery in Oilfields. *Acta Petrolei Sinica, 28,* 73-78.

Han, G. M., Dai, Z. G., Yang, J. L., Cao, M. J., Yan, J. Z., & Liu, H. Y. (2017). A Method for Optimizing Liquid Production Rate Under Multi-Well Interference Based on Balanced Displacement. *Oil Drilling & Production Technology, 39,* 254-258.

Hu, W. R. (2007). Overview of Secondary Development Technologies for Petroleum in China. *Special Oil & Gas Reservoirs, 14,* 1-4+16.

Jia, X. F., Li, Q. Z., Yang, J. et al. (2012). A Method for Determining Injection Volume of Separate-Layer Adjustment Water Injection Wells Based on Remaining Oil Distribution. *China Offshore Oil and Gas, 24,* 38-40.

Li, C. L., Deng, P., Zhu, S. Y., & Liu, D. H. (2018). The Equivalent Principle of Seepage Circles. *Xinjiang Petroleum Geology, 39,* 717-721.

Ma, K. Q., Chen, C. L., & Liu, Y. X. (2019). A Zonal Injection Allocation Method for Water Injection Wells Based on Interlayer Balanced Displacement. *Special Oil & Gas Reservoirs, 26,* 109-112.

Sun, Q., Shi, H. F., Ling, H. C., Pan, J., & Deng, Q. (2020). A Method for Adjusting Liquid Production Rate of Balanced Displacement in Narrow Strip Heavy Oil Reservoirs. *Special Oil & Gas Reservoirs, 27,* 120-124.

Sun, Z. B., Li, Y. P., Jia, X. F., Li, Y. L., & Zhang, G. H. (2018). A Method for Determining Zonal Injection Allocation in Water Injection Wells of High-Water-Cut Oilfields Based on Quantitative Characterization of Displacement. *Petroleum Drilling Techniques, 46,* 87-91.

Wang, D. L., Guo, P., Wang, Z. H., He, H. Y., & Fu, W. F. (2011). Study on Balanced Displacement Effect of Injection-Production Well Groups in Heterogeneous Reservoirs. *Journal of Southwest Petroleum University (Natural Science Edition), 33,* 122-125.

Yan, K., Zhang, J., Wang, B. Z. et al. (2015). Study on Adjustment Method of Balanced Waterflooding in Plane Heterogeneous Reservoirs. *Special Oil & Gas Reservoirs, 22,* 86-89.

Yang, M., Liu, Y. X., Chen, C. L. et al. (2019). A Plane Balanced Displacement Method for Irregular Injection-Production Well Patterns in Complex Fault-Block Reservoirs. *Fault-Block Oil & Gas Field, 26,* 756-760.

Zhang, J. G., Du, D. F., Hou, J. et al. (2006). *Seepage Mechanics of Oil and Gas Reservoirs*. China University of Petroleum Press.

Zhou, S. W. (2007). Research and Application of a New Model for Efficient Development of Offshore Heavy Oil. *Journal of Southwest Petroleum University, 29,* 1-4.

Zhou, S. W. (2009). *Practice of Typical Oilfield Development in China's Offshore Areas*. Petroleum Industry Press.