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Study on Numerical Simulation of Reservoir Fine Water Injection Development Considering Reservoir Heterogeneity

Bingyong Zhang

PetroChina Qinghai Oilfield No.1 Oil Production Plant, Dunhuang, Gansu, China

Abstract: Reservoir heterogeneity includes macroscopic interlayer, intralayer and plane heterogeneity, as well as microscopic differences in pore structure and wettability, which significantly affect water flooding efficiency and remaining oil distribution. By collecting geological, dynamic and rock fluid data, a fine geological model is constructed, and the reservoir characteristics are accurately described by using mixed grid strategy and discrete fracture network model. In the numerical simulation, the black oil model considering the influence of dissolved gas is selected and the non-Darcy flow is modified. In the design of development scheme, the water injection mode, water injection horizon selection, dynamic control of water injection speed and injection-production ratio optimization strategy are optimized. The results show that the oil recovery is increased by 6.2% by stratified controlled water injection compared with uniform water injection, and the oil recovery is further increased by 2.5% by dynamic optimization scheme. Reservoir heterogeneity has a significant impact on the development effect. For every 0.1 increase in permeability variation coefficient, the sweep efficiency of water flooding decreases by about 8%. Through dynamic injection-production regulation and intelligent separate injection technology, the optimization scheme has significantly improved the oil recovery and economic benefits.

Keywords: Reservoir Heterogeneity; Numerical Simulation; Reservoir Fine Water Injection; Recovery Ratio.

1. Introduction

Reservoir heterogeneity, including macroscopic interlayer, intralayer and plane heterogeneity and microscopic differences in pore structure and wettability, makes the fluid flow in the reservoir extremely complicated, which seriously affects the water flooding efficiency and the distribution of remaining oil [1]. Considering reservoir heterogeneity, the design and optimization of reservoir development scheme is of great significance for improving oil recovery and reducing development cost. Traditional reservoir engineering methods are often difficult to accurately describe and predict the specific impact of reservoir heterogeneity on water injection development effect, while reservoir numerical simulation technology provides an effective means [2-3]. Through numerical simulation, a fine geological model is established to simulate the fluid flow process under different development schemes, so as to optimize the water injection development scheme and improve oil recovery.

In recent years, scholars at home and abroad have made remarkable progress in reservoir heterogeneity research, reservoir numerical simulation technology and water injection development scheme optimization. However, how to characterize reservoir heterogeneity more accurately, how to effectively integrate it into reservoir numerical simulation, and how to optimize water injection development scheme through numerical simulation technology are still problems that need to be further studied and explored. Therefore, on the basis of considering reservoir heterogeneity, this paper studies the numerical simulation of reservoir fine water injection development. By establishing a fine geological model and designing a reasonable numerical simulation scheme, this paper analyzes the specific influence of reservoir heterogeneity on water injection development effect, and discusses how to improve oil recovery by optimizing water injection development scheme.

2. Model Building

2.1. Data Collection and Processing

It mainly includes geological data, dynamic data and rock fluid data. Geological data include the depth map of structural top surface, fault distribution, sedimentary facies zone division, permeability and porosity field (considering variation coefficient), and fracture development characteristics; Dynamic data involves historical production of production wells (oil and water), injection pressure and water volume of water injection wells, and pressure test data (PLT, RFT); The data of rock fluid covers the relative permeability curve, capillary pressure and PVT parameters of fluid in the phase separation zone (considering pressure sensitivity). In order to characterize the heterogeneity, the permeability variation coefficient is used to quantify the heterogeneity between layers and within layers, and a tensor model of permeability anisotropy (kx: ky: kz=1:0.5:0.1) is established to accurately describe the characteristics of underground reservoirs [4-5].

2.2. Geological Model Construction

The grid system design adopts the hybrid grid strategy, and the corner grid is used in the main area (the size is 50m×50m×2m), while the local high permeability strips are encrypted by PEBI grid (the minimum grid size is 10m). Vertical stratification is divided into small layers [6] with a single layer thickness of less than 3 meters according to the sedimentary rhythm. In attribute modeling, porosity field is generated by sequential Gaussian simulation, permeability is simulated by collaborative kriging method based on sedimentary facies, and fracture system is embedded into the whole model by using discrete fracture network (DFN) model to realize accurate description of complex geological characteristics.

2.3. Numerical Model Establishment

The black oil model considering the influence of dissolved gas is selected, and the non-Darcy flow is modified, using Forchheimer equation [7]. The permeability tensor of the main permeability direction is set according to the river course trend, and the relative permeability endpoint values are set according to the permeability of different areas, specifically: kro@Sw=0.3 in the high permeability area and kro@Sw=0.5 in the low permeability area.

3. Numerical Simulation Scheme Design

3.1. Optimization of Water Injection Mode

According to the geological conditions, different well patterns are selected, and determinant water injection is used in the river sand body development area, while irregular water injection is used in the fault complex area. Well location layout follows specific principles, including setting water injection wells at least 150 meters away from the boundary of high permeability zone and deploying production wells in the permeability gradient change zone (i.e. the transition zone with permeability of 50-200mD) to improve water injection and oil production efficiency [8].

3.2. Water Injection Horizon Selection

Table 1. Water injection horizon selection and strategy

Layer system name	Permeability range	Water injection strategy
Class I layer	k > 500 mD	Limited flow water injection
Class II layer	200 mD ≤ k ≤ 500 mD	Main water injection layer
Class III layer	k < 200 mD	Suspend development

The reservoirs are divided into three categories by adopting the development strategy of vertical layering (Table 1). Among them, I-type layer (with permeability greater than 500mD) is subject to restricted water injection, II-type layer (with permeability between 200 and 500mD) is the main water injection layer, and III-type layer (with permeability less than 200mD) is put on hold. In order to optimize the water injection effect of each layer, ICD intelligent completion technology is adopted to control water injection in different layers, and the proportion of water injection in high permeability layers is not more than 30%.

3.3. Dynamic Control of Water Injection Rate

Stage control standards are shown in Table 2:

Table 2. Stage control standard

development phase	Water injection speed (m^3/d)	Keep the pressure level
Initial period (0-3 years)	80-120	Original pressure 90%
Mid-term (4-8 years)	150-200	Original pressure 95%
Late period (> 8 years)	80-100	Original pressure 85%

It is stipulated that the change rate of single well water injection rate shall not exceed 10% per month. If the increase rate of water content exceeds 5% per quarter, the water injection rate should be reduced by 20%.

3.4. Optimal Design of Injection-Production Ratio

The optimization design of injection production ratio is based on theoretical calculations and dynamic adjustment strategies. Firstly, calculate the theoretical injection production ratio using the formula: Theoretical injection production ratio=(underground crude oil volume coefficient x oil recovery rate)/(water injection efficiency x sweep coefficient), and adjust it by the heterogeneity correction factor η (equal to 0.8 x (Vk) ^ (-0.3)) [9]. The initial injection production ratio is set at 1.2 times the value of η. During the production process, if an annual decrease in pressure exceeding 0.5 MPa is observed, the injection production ratio will be increased by 0.1; If the rate of increase in moisture content exceeds 3% per quarter, the injection production ratio will be reduced by 0.15.

4. Analysis of Numerical Simulation Results

4.1. Comparison of Basic Development Effects

Compared with uniform water injection, layered regulation water injection can improve the oil recovery by 6.2%, and the dynamic optimization scheme can further increase the oil recovery by 2.5%, which verifies the effectiveness of the reservoir heterogeneity adaptive development scheme (see Table 3).

Table 3. Comparison of development indexes of different water injection schemes (20-year forecast)

Scheme type	Recovery ratio (%)	Moisture content (%)	Pressure retention rate (%)	Breakthrough time of water drive front (year)
Uniform water injection	32.5	92.3	78.2	3.8
Layered regulation water injection	38.7	88.1	85.6	5.2
Dynamic optimal water injection	41.2	85.4	89.3	6.5

4.2. Analysis on the Influence of Reservoir Heterogeneity

As shown in Figure 1, when Vk>0.7, the decline slope of oil recovery increases significantly ($\Delta\eta \approx 6\%/0.1Vk$). The water cut of highly heterogeneous reservoir (Vk=0.9) rises 40% faster than that of homogeneous reservoir. The water content of high permeability layer (k=500mD) exceeded 90% after 3 years of water injection. The water breakthrough time of low permeability layer (k=50mD) is delayed to 8 years. The interlayer contradiction leads to the overall oil recovery loss of about 12.7%. See Figure 2 for the interference phenomenon between different permeability ratio layers.

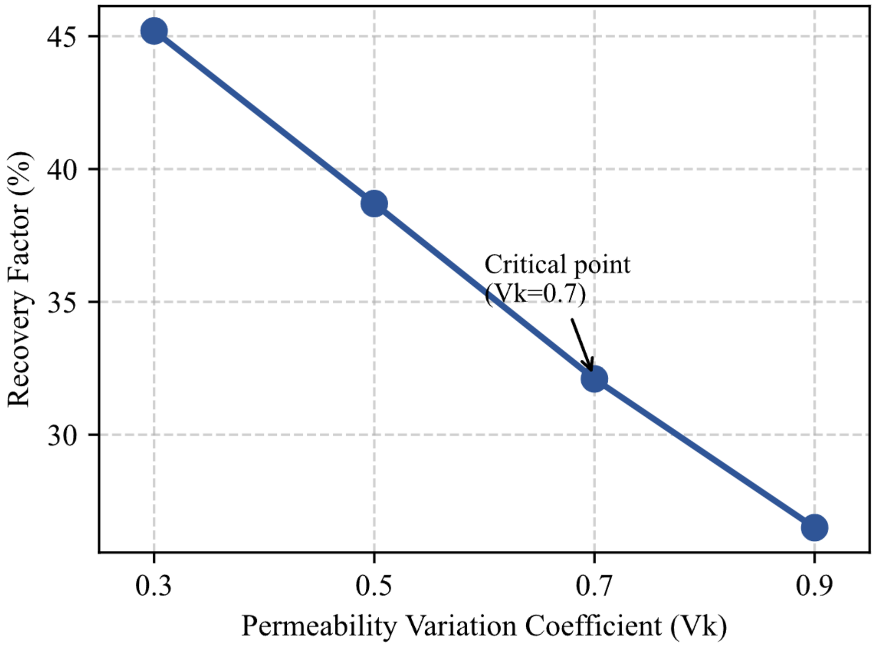

Figure 1. Relationship curve between permeability variation coefficient and oil recovery

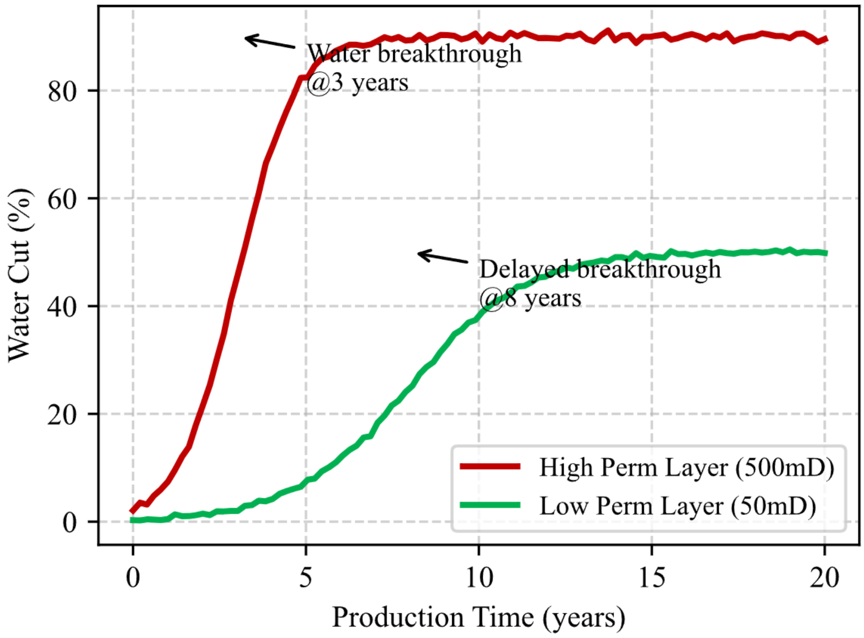

Figure 2. Interlayer interference moisture content curve

4.3. Optimization Effect of Water Injection Scheme

According to the optimization results of orthogonal experimental design (L9) (Table 4), different injection-production ratios and well pattern types have significant effects on oil recovery. The recovery ratio of injection-production ratio of 1.1 plus determinant well pattern is 36.8%, which is the least satisfactory. The recovery ratio of injection-production ratio of 1.3 combined with area well pattern reaches 39.2%, and the effect is good; The strategy of dynamic adjustment combined with intelligent separate injection has the highest recovery rate of 41.5%, making it the best scheme. This shows that increasing the injection-production ratio and selecting the appropriate well pattern type, especially combining dynamic adjustment with intelligent separate injection, are the best strategies to improve oil recovery.

Table 4. Optimization results of orthogonal experimental design (L9)

Factor combination	Recovery ratio (%)	Weighted sorting
Injection-production ratio 1.1+ determinant	36.8	4
Injection-production ratio 1.3+ area	39.2	2
Dynamic adjustment+ intelligent dispensing	41.5	1

Reservoir heterogeneity has a significant impact on reservoir development, especially when the permeability ratio exceeds 5, it will cause serious interlayer interference. When the coefficient of variation increases by 0.1, the sweep efficiency of water flooding will decrease by about 8%, and the ineffective water circulation caused by high permeability channels will reach more than 30%. In the optimized scheme, the pressure retention rate can be increased to over 89% through dynamic injection-production regulation, and the water injection rate of high permeability layer can be reduced by 42% with the help of intelligent separate injection technology, so that the advancing speed of water drive front can be reduced from 1.5m/d to 0.8 m/d. In addition, every 1% increase in oil recovery can increase recoverable reserves by 5.2×10^4 tons, and the optimized scheme can reduce the cost of barrel oil by $3.2 compared with the basic scheme.

In order to further improve the development effect and economic benefits, it is suggested to establish a real-time early warning mechanism of permeability variation coefficient and start dynamic regulation when Vk is greater than 0.6. The "step-by-step" injection-production ratio adjustment strategy is adopted, that is, it is set at 1.3 in the initial stage, adjusted to 1.1 in the middle stage, and then reduced to 0.9 in the later stage. At the same time, profile control and flooding agent injection wells are deployed at the front edge of high permeability zone, and the polymer concentration is set at 1500 mg/L. The research shows that by finely characterizing permeability field and optimizing dynamic water injection, oil recovery can be significantly improved by 8-12 percentage points in strongly heterogeneous reservoirs, and the follow-up research should pay attention to the application of adaptive grid encryption technology and real-time data assimilation algorithm.

5. Conclusion

Reservoir heterogeneity significantly affects reservoir development. The water content of highly heterogeneous reservoir (Vk=0.9) rises 40% faster than that of homogeneous reservoir, and the sweep efficiency of water drive decreases about 8% for every 0.1 increase of variation coefficient. Optimizing water injection development scheme, such as increasing injection-production ratio, selecting suitable well pattern type and combining dynamic adjustment with intelligent injection distribution strategy, can effectively improve oil recovery. Compared with uniform water injection, layered regulation water injection can improve oil recovery by 6.2%, while dynamic optimization scheme can further increase oil recovery by 2.5%. In addition, through orthogonal test design, it is found that the strategy of dynamic adjustment combined with intelligent separate injection has the highest recovery rate, reaching 41.5%. In order to further improve the development effect and economic benefits, it is suggested to establish a real-time early warning mechanism of permeability variation coefficient and start dynamic regulation when Vk is greater than 0.6. The "step-by-step" injection-production ratio adjustment strategy is adopted, that is, it is set at 1.3 in the initial stage, adjusted to 1.1 in the middle stage, and then reduced to 0.9 in the later stage. At the same time, profile control and flooding agent injection wells are deployed at the front edge of high permeability zone, and the polymer concentration is set at 1500 mg/L. These measures can significantly improve oil recovery by 8-12 percentage points in strongly heterogeneous reservoirs and reduce the cost of barrel oil by $3.2. Numerical simulation of reservoir fine water injection development considering reservoir heterogeneity is of great significance for improving oil recovery and reducing development cost. By optimizing the water injection development scheme, the challenges brought by reservoir heterogeneity can be effectively met and the efficient development of the reservoir can be realized.

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