A novel optimization method based on interlayer equilibrium displacement for heterogeneous reservoir with high efficiency

Fengyang Han 1, Min Wang 1,*, Hongxia Sun 2, Baoguo Tan 2, Yumin Yao 1, Zhifeng Liu 1, Anfeng Shi 1, Xiaohong Wang 1

1 Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, China
2 Exploration and Development Research Institute, Shengli Oilfield Company, China Petroleum & Chemical Corporation SINOPEC, Dongying, China

*Corresponding author e-mail: wang159@ustc.edu.cn

Abstract. In order to formulate the optimal control scheme of injection and production rates for heterogeneous reservoir scientifically and effectively, so as to realize the efficient development of heterogeneous reservoirs, a production optimization method based on interlayer equilibrium displacement for heterogeneous reservoir is proposed. The proposed method decomposes the origin production optimization problem into multiple easy-to-solve sub-problems. Solving the sub-problems can obtain the approximate optimal solution of the origin production optimization problem at a small computational cost. Then use the approximate optimal solution as the initial solution, the number of iteration steps required for origin optimization problem will be greatly reduced. The proposed method is applied to an actual reservoir production optimization. The results show that the method can greatly shorten the calculation time and increase the calculation efficiency by 3 times while ensuring the optimization effect.

1. Introduction
In the process of waterflooding development, due to the heterogeneity of the reservoir, the injected water flows faster in the high-permeability area, which makes the crude oil in the low-permeability area unable to be affected effectively, and eventually causes un-equilibrium displacement [1]. Adjusting and controlling the flow rate of injection and production wells is an important means to relieve un-equilibrium displacement and tap the potential of reservoir production [2]. By combining optimization algorithms and reservoir numerical simulation technology, the optimal injection-production control scheme can be calculated [3]. However, the actual reservoir model has a huge grid size and number of wells, which makes injection-production optimization require a lot of calculations. In order to reduce the time-consuming of calculation, scholars explored a series of methods. For example, the use of reservoir engineering methods can provide a good initial solution for the problem of injection allocation optimization for a layered injection well [4], thereby reducing the number of iteration steps required in the optimization process; Drawing on the idea of divide and conquer, the large-scale reservoir block is artificially divided into multiple small-scale blocks [5], thereby reducing the calculation. However, this method ignores the mutual influence between blocks, and the result often deviates from the optimal solution. The structure of this article is arranged as follows, in the section 2, a new and efficient method
of injection-production optimization is introduced, along with comparison conventional adjustment and optimization schemes. In section 3, a 3D reservoir case in China is performed to test the efficiency of the proposed method. Conclusions are given in section 4.

2. The novel optimization method and comparison schemes

2.1. Injection-production optimization method of heterogeneous reservoir based on interlayer equilibrium displacement and lateral optimization

Firstly, adopts the interlayer flow distribution method based on the remaining recoverable reserves to distribute the flow of injection-production wells in each layer. Then split the 3D reservoir into multiple 2D layers (Figure 1), and optimize flow rate of each well’s interval layer by layer.

The calculation results of the above steps can be used as the iterative initial value for the optimization of injection-production parameters in the high-water-cut stage of the 3D heterogeneous reservoir. Finally realize the optimization of the production plan for the 3D heterogeneous high-water-cut reservoir. The optimization process proposed in this paper is shown in Figure 2.

![Figure 1. Schematic diagram of reservoir decomposition](image)

![Figure 2. Flow chart of the method proposed in this paper](image)

2.1.1. Flow rate allocation determination method based on equilibrium displacement between layers.

The remaining recoverable reserves method distributes the flow rate of each layer according to the weight of the remaining recoverable reserves of each layer [6]. This method can improve the producing degree of the layer with low permeability and more remaining recoverable reserves. The mathematically described is

\[
Q_{l\alpha} = \frac{M_l(1 - R_i)}{\sum_{l=1}^{3} [M_l(1 - R_i)]} Q_{\text{tot}}, \quad \alpha = I, P
\]

Where \(Q_{l\alpha}\) and \(Q_{\text{tot}}\) represent the water injection or liquid production rate of the \(l\)th layer and the total water injection or liquid production rate of the three-dimensional reservoir, respectively, \(\text{m}^3/\text{day}\).
M_i shows the remaining recoverable reserves of the i-th layer; R_i indicates the degree of recovery and reserves of the i-th layer in the current control step.

2.1.2. Injection and production optimization layer by layer. Considering that the grid scale of the real reservoir model is huge, resulting in a huge amount of calculation for reservoir numerical simulation, we disassembled the complete reservoir into multiple independent layers, and optimize flow distribution between wells layer by layer. Take the flow rate of each well’s interval in each layer as the variable to be optimized, and the total oil production of each layer as the objective function. The mathematical description of the plane distribution optimization of the i-th layer is

$$J^\text{opt}_i(U_i, Y_i^0) = \sum_{w=1}^{N^w} q_{i,w}^p$$

(2)

subjected to

$$\lambda_{i,w}^a \leq u_{i,w}^a \leq \lambda_{i,w}^b$$

(3)

$$\sum_{w=1}^{N^w} u_{i,w}^a = Q_i^\text{w}$$

(4)

where, $J^\text{opt}_i$ is the objective function, which represents the cumulative oil production of the i-th layer in the current control step, $10^3$ sm$^3$; $u_{i,w}^a$ is the variable to be optimized, which represents the flow rate of the section connected to the i-th layer of the w-th injection or production well, m$^3$/day; $Q_i^\text{w}$ is the total injection or production flow of i-th layer obtained by the method introduced in section 2.1.1, m$^3$/day; $Y_i^0$ represents the state parameters of the grid of the i-th layer at the initial time of the control step, such as saturation and pressure; $q_{i,w}^p$ indicates the cumulative oil production produced by of the w-th well’s interval, which connected to the i-th layer in the control step, $10^3$ kg; $\lambda_{i,w}^a$ and $\lambda_{i,w}^b$ are the upper and lower flow rate limits of each well’s interval.

2.1.3. Injection-production control optimization of 3D reservoirs. The above steps can be used as a pretreatment method that can provide an approximate optimal injection-production control scheme for the three-dimensional reservoir injection-production optimization problem. With this scheme as the initial value of the optimization problem, only a few iterations are needed to get the real optimal solution. In the injection-production optimization of three-dimensional reservoirs, the maximum cumulative oil production of the reservoir is used as the objective function of optimization, the flow rate of each interval of each injection or production well is used as the variable to be optimized. The mathematical description of the optimization problem is

$$J^\text{opt}(U, Y^0) = \sum_{w=1}^{N^p} q_{w}^p$$

(5)

subjected to

$$U = \begin{bmatrix} u_{1,1}^1 & \cdots & u_{1,N_1}^1 & u_{1,1}^p & \cdots & u_{1,N_1}^p \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ u_{w,1}^1 & \cdots & u_{w,N_1}^1 & u_{w,1}^p & \cdots & u_{w,N_1}^p \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ u_{1,1}^1 & \cdots & u_{1,N_1}^1 & u_{1,1}^p & \cdots & u_{1,N_1}^p \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ u_{w,1}^1 & \cdots & u_{w,N_1}^1 & u_{w,1}^p & \cdots & u_{w,N_1}^p \end{bmatrix}$$
The total injection or production flow rate should meet the the constraint condition (6) where \( n_s \) represent the number of intervals of the \( w \)th oil well.

2.2. Comparison schemes

1. Basic scheme: the total injection or production flow rate is evenly distributed to each well. The flow distribution of each interval of each well is determined according to the 'K-H' method [7];

2. Traditional optimization method: The basic scheme is used as the initial solution of the subsequent optimization iteration, and the 3D reservoir injection-production optimization method introduced in section 2.1.3 is directly used to calculate the optimal injection-production control scheme;

3. The proposed optimization method: use the methods introduced in sections 2.1.1 and 2.1.2 to determine the initial solution for subsequent optimization iterations, and then use the injection-production optimization method for three-dimensional reservoirs introduced in section 2.1.3 to calculate the optimal injection-production control scheme.

3. Numerical tests

In this section, we use realistic reservoir’s 3D numerical model to test the efficiency of the proposed production optimization method. For comparison purpose, the calculations of other conventional adjustment and optimization schemes, listed in section 2, are performed in this example. Consider reservoir model given in Figure 3, which is taken from Shengli Oil Field Xin-42 reservoir block in China. 7 inject wells and 12 production wells was arranged in this reservoir, and each well has 6 intervals. The total injection rate and total liquid production rate of are 450m³/day. After 1,000 days of waterflooding development, the oilfield entered a high water cut stage. After that, with 50 days as a control step, the next 500days’ injection-production control scheme is optimized step by step.

![Fig. 3](image)

(a) Initial saturation field and well pattern management, (b) Permeability distribution of top layer, middle layer, bottom layer

| Scheme | FOPT(1000-1500day)/10³ sm³ | cpu_time/h |
|--------|---------------------------|-----------|
| 1      | 79.1                      | -         |
| 2      | 90.94                     | t3=50.8   |
| 3      | 90.94                     | t3=15.8   |

Table 1. Performance of schemes.
From Table 1, the calculation time of optimization Scheme 2 and Scheme 3 are 50.8 hours and 15.8 hours respectively, that is, the optimization efficiency of the proposed method is 3.2 times that of the traditional method. Comparing the cumulative oil production of each scheme, it can be seen that the cumulative oil production of scheme 2 and scheme 3 is basically the same, and it is significantly higher than scheme 1, which shows he proposed method can greatly increase the calculation efficiency while ensuring the optimization effect.

4. Conclusion
In this article, under the condition of fixed total fluid rate, the production optimization problem of heterogeneous reservoir is studied. By decomposing the origin reservoir production optimization problem into multiple easy-to-solve sub-problems, a novel optimization method considering equilibrium is proposed. The proposed method can provide an approximate optimal solution for the production optimization of heterogeneous reservoir at a small computational cost, and reducing the the number of iterative steps needed for subsequent optimization, so as to improve the efficiency of production optimization. The actual reservoir injection-production control optimization calculation example shows that compared with other methods, the proposed method can greatly reduce the calculation time and increase the calculation efficiency by 3 times while ensuring the optimization effect.

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