A New Method for Plane Equilibrium Injection-production Adjustment of Water-drive Reservoir

Guangyi Sun 1, Yingxian Liu 1, Huijiang Chang 1, Xiaoming Chen 1, Chi Dong 2, *
1Bohai Petroleum Research Institute, China National Offshore Oil Corp, Tianjin, 300459, China
2MOE Key Laboratory of Enhanced Oil Recovery, Northeast Petroleum University, Daqing, China

*Corresponding author e-mail: nepuc2006@163.com

Abstract. In view of the lack of theoretical research on plane equilibrium injection-production adjustment in water drive reservoir, the production prediction method under the condition of variable pressure difference of production well is deduced according to Buckley Leverett non-piston displacement theory. Taking the same degree of extraction as the goal, the adjustment method of plane equilibrium injection-production per unit time is put forward. The evaluation coefficient of the optimal equilibrium injection-production scheme is defined, which can guide the optimization of the equilibrium injection-production scheme. Through theoretical model analysis, it is considered that the adjustment method of plane equilibrium injection-production is reasonable and reliable. Seven kinds of adjustment schemes are designed for BZ oilfield in Bohai Sea. Of equilibrium displacement time. When the equilibrium displacement time is more than 10 years, the increment of recovery degree slows down to about 1.8%. Equilibrium injection-production adjustment was carried out for 1195 sand body in BZ oilfield. The sand body increased oil by 25m³/d per day, and the natural decline rate decreased by 1.1%.

Keywords: equilibrium injection-production adjustment; water flooding adjustment; equilibrium displacement; injection allocation optimization; liquid-production adjustment.

1. Introduction
Equilibrium displacement is the target of injection in water drive reservoir. In the early stage of oilfield development, Due to the influence of reservoir heterogeneity, for regular well pattern, vector well pattern is generally used for well layout. Design different production pressure difference according to different permeability in different directions, so as to achieve injection production balanced displacement [1-7]. In the oilfield development stage, Cui Chuanzhi, Ma kuijian and others studied the vertical or interlayer equilibrium displacement method. The core idea of the vertical equilibrium displacement of water injection well is to adjust the interlayer water injection in a certain period of time, so that the remaining oil saturation of each layer is the same [8-14]. There are few researches on plane equilibrium displacement, Han Guangming put forward the concept of breakthrough coefficient of...
displacement, and put forward the optimization method of liquid-production under multi well interference based on equilibrium displacement [15], which can guide the adjustment of plane equilibrium injection and production, but the changing law of production pressure difference to reach equilibrium flooding is not described. Cui Chuanzhi proposed to divide the plane well pattern into different flow units, study the injection-production pressure difference of different flow units through the flow tube method, and propose the plane equilibrium injection-production method [16], but in the process of application, the calculation of flow tube method is complicated. Taking the same degree of water cut as the goal, changhuijiang puts forward the plane equilibrium displacement method of irregular well pattern [17]. However, in the process of oilfield development, wells with high water cut often have different recovery degree or displacement degree, because which is closely related to reservoir reserves and heterogeneity. Based on the previous research results, according to Buckley Leverett non-piston water drive theory, the productivity prediction formula of production wells under the condition of variable pressure difference is derived, and a new method of plane equilibrium injection-production adjustment is proposed.

2. Plane equilibrium injection-production adjustment method

2.1. Plane equilibrium displacement principle

Equilibrium displacement refers to the same displacement degree (residual oil saturation or recovery degree) of injected water in each area of the plane. Realizing equilibrium displacement can improve the injected water wave and its range, reduce the inefficient and ineffective circulation of water injection, and improve the development effect of water injection. Due to the influence of reservoir heterogeneity, as long as the displacement degree of each injection production well connection is equal, it can be considered that (partial) equilibrium displacement has been achieved.

For oil fields, in a period of time, Take some measures to stabilize oil and control water for the wells with high water cut and high recovery degree, and optimize the production system reasonably, so that the recovery degree of each production well is the same, which is the principle of the adjustment of injection production in the plane equilibrium of oilfield. How to achieve the same recovery degree in the specified time for different production wells is a challenging job. First of all, it is necessary to establish a production well production prediction method with variable pressure difference.

2.2. Production prediction of production wells with variable pressure difference

According to Buckley Leverett non-piston water drive theory, dimensionless production index of production wells can be expressed as follows:

$$ J_{DL} = \frac{K_{ro}}{K_{ro}(S_{wi})} + \frac{K_{ro}B_o\mu_o}{K_{ro}(S_{wi})B_w\mu_w} \quad (1) $$

In the formula, $J_{DL}$ is dimensionless recovery index. $K_{ro}(S_{wi})$, $K_{ro}(S_{wi})$ are the relative permeability of oil phase and water phase at irreducible water saturation, respectively. $B_o$, $B_w$ are volume coefficient of oil and water, respectively.

There is the following relationship between dimensionless production index $J_{DO}$ and dimensionless production fluid index $J_{DL}$:

$$ J_{DO} = J_{DL} \left(1 - f_w(S_w)\right) \quad (2) $$

$J_{DO}$ is dimensionless production index. $f_w(S_w)$ is water cut ratio, %.

The recovery degree $R$ of production well and average water saturation $\bar{S}_w$ of well control area can be expressed by formula3:
\[ R = \frac{S_w - S_{wi}}{1 - S_{wi}} \]  

(3)

In the formula, \( R \) is recovery percent,\%. \( S_w \) is average water saturation, \( S_{wi} \) is water saturation. According to the welle equation

\[ \bar{S}_w = S_w + \frac{1 - f_w(S_w)}{f'_w(S_w)} \]  

(4)

Combining formula 3 and 4, the derivative of recovery degree \( R \), water cut \( f_w(S_w) \) and water content derivative \( f'_w(S_w) \) can be expressed as

\[ R = \frac{f'_w(S_w)(S_w - S_{wi}) + 1 - f_w(S_w)}{1 - S_{wi}} \]  

(5)

According to the definition of partial discharge equation,

\[ f'_w(S_w) = \frac{Aabe^{S_w}}{(1 + Aae^{-aS_w})^2} \]  

(6)

In the formula, \( A = \frac{\mu_o K_{ro}}{\mu_w K_{rw}} \), Dimensionless. \( K_{ro} \), \( K_{rw} \) are relative permeability of oil phase and water phase, respectively. \( \mu_o \), \( \mu_w \) are viscosity of oil and water, mPa·s.

Given the relative permeability curve, the relation between recovery degree and water content can be obtained by taking formula 6 into formula 5.

The natural decline rate of production well changes with the rise rate of water cut. For the production condition with constant liquid volume, the natural decline rate \( D_t \) can be expressed as

\[ D_t = \frac{Q}{N_R} f'_w(S_w) \]  

(7)

In the formula, \( Q \) is liquid production rate, m³/d. \( N_R \) is produced geological reserves, 10⁴m³.

It is assumed that the daily oil production of production wells at any time \( t \) is \( Q_{ot} \), according to equation 7, the daily oil production of production wells at \( t + 1 \) time can be calculated as

\[ Q_{ot+1} = Q_{ot} \cdot (1 - D_t) \]  

(8)

On the premise that the liquid production of production well is constant instantaneously, at present \( Q_{Lt+1} = Q_{Lt} \). According to formula 1-8, the \( f_{wtr+1}, f'_{wtr+1}, D_{tr+1}, J_{DOr+1}, J_{DLr+1} \) at time \( t + 1 \) can be calculated.

If the production pressure difference of production well at the set time \( t + 1 \) is \( \Delta P_{r+1} \), then the variation range of production well fluid volume \( \omega \) is:

\[ \omega = \frac{(J_{DOr+1} \cdot \Delta P_{r+1})}{(J_{DOr} \cdot \Delta P_{r})} \]  

(9)
It is considered that if the instantaneous water cut of production well is constant time $t$, the liquid production, oil production and water cut at time $t + 1$ are respectively

$$Q_{L,t+1} = \omega \cdot Q_{L,t}, \quad Q_{\omega,t+1} = \omega \cdot Q_{\omega,t}, \quad f_{w,t+1} = \frac{Q_{f,t+1}}{Q_{w,t+1}}$$  \hspace{1cm} (10)

Equation 10 is the prediction result of production well with variable pressure difference and water cut.

2.3. Plane equilibrium adjustment method of injection-production

Assuming that there are $x$ production wells in the oilfield, the water cut of each production well can be determined by $f_{w_1}, f_{w_2}, ... f_{w_x}$ Express when time $t$. According to formula 5, the recovery degree is $R_{1,n}, R_{2,n}, ... R_{x,n}$. Set the recovery degree $R_{n}$ of each production well at the same time, which means equilibrium adjustment. When the production differential pressure is given, According to formula 8-10, we can get $Q_{f,t}, f_{w,t}, f_{o,t}, Q_{L,t}, Q_{w,t}$ of the moment $t + 2 ... t + n$. Each production well needs to continuously adjust the production pressure difference according to its dimensionless production and production law, including enlarging and reducing the pressure difference, so as to realize the adjustment of production fluid structure of production wells. At the same time, according to the demand of injection-production ratio, the water injection quantity is adjusted to realize the plane equilibrium displacement of oilfield. The new method of plane equilibrium injection-production has wide applicability, especially for irregular well pattern. The calculation process can be realized by computer programming to improve the calculation efficiency.

2.4. Determination method of optimal equilibrium injection-production plan

For oilfield development, the adjustment of injection-production will be restricted by many factors, such as the capacity of fluid production and treatment, the capacity of water injection, the condition of production wells and so on. These factors should be fully considered when making a reasonable equilibrium injection-production adjustment plan. The production index reflected by the above factors can be summed up as the collaborative relationship between the production (liquid) speed and the increase of stage recovery degree, that is to determine the reasonable production (liquid) speed, so as to maximize the increase of stage recovery degree.

In order to select the optimal balanced injection-production adjustment scheme, the evaluation coefficient $\lambda$ of the optimal balanced injection-production scheme is defined here

$$\lambda = \frac{\Delta EOR}{\Delta FLPR}$$  \hspace{1cm} (11)

In the formula, $\lambda$ is the evaluation coefficient of the optimal balanced injection production scheme, dimensionless. $\Delta EOR$ is the increase of stage recovery degree, %. $\Delta FLPR$ is the increase of stage production speed, %. The larger the $\lambda$, the higher the recovery rate can be achieved by adjusting the minimum liquid volume in a certain period of time, so as to maximize the effect of injection-production adjustment.

3. Application examples

BZ oilfield is a shallow water delta sedimentary oilfield in Bohai Sea with strong plane heterogeneity. At present, it has entered the stage of high water cut development, with a comprehensive water content of 81% in 2018. Due to the influence of reservoir heterogeneity, irregular injection production well pattern and unbalanced plane water drive, local seepage dominant channel is formed and the development effect is poor.

In order to improve the effect of waterflood development, the equilibrium injection-production adjustment scheme is designed for the oilfield in 2019, with 7 balanced injection production adjustment
schemes (Table 1). The results show that, for BZ oilfield, with the increase of the time to reach equilibrium displacement, the overall increase of oil recovery of equilibrium displacement scheme is larger than that of non equilibrium displacement scheme. When the equilibrium displacement time is more than 10 years, the growth rate of recovery degree slows down to about 1.8%. That is to say, for this oilfield, the recovery factor of water drive can increase by 1.8% in theory after realizing injection-production equilibrium displacement. Through the optimization of the equilibrium injection-production adjustment scheme, when the oil production rate is 1.9%, $\lambda$ is the largest, which is 1.2, and the increase rate of the stage recovery degree is 1.6%. From the perspective of the maximum benefit, the equilibrium injection-production adjustment scheme is the best.

Table 1. Equilibrium injection-production adjustment scheme design of BZ Oilfield

| Scheme | Reach equilibrium displacement time (year) | Recovery percent (%) | Increase in recovery (%) | $\lambda$ |
|--------|-----------------------------------------|----------------------|-------------------------|----------|
|        |                                         | Unbalanced displacement | Equilibrium displacement |          |
| 1      | 2                                       | 26.2                 | 27.1                    | 0.9      | 0.3    |
| 2      | 4                                       | 29.5                 | 30.7                    | 1.2      | 0.5    |
| 3      | 6                                       | 32.1                 | 33.5                    | 1.4      | 0.7    |
| 4      | 8                                       | 34.2                 | 35.8                    | 1.6      | 1.2    |
| 5      | 10                                      | 35.8                 | 37.6                    | 1.8      | 0.7    |
| 6      | 12                                      | 37.1                 | 38.9                    | 1.8      | 0.8    |
| 7      | 14                                      | 37.9                 | 39.7                    | 1.8      | 0.7    |

Field test of balanced injection production adjustment for main sand body 1195 in BZ Oilfield. The adjustment starts from February 10, 2019, and by the end of May, the production well has implemented 10 times of liquid production structure adjustment (6 times of liquid extraction and 4 times of liquid limit), 9 times of water injection well allocation and injection volume optimization adjustment, the overall liquid production and water injection volume increased by 370m³/D respectively (Fig. 1), and the oil production rate of sand body increased from 1.8% to 1.9%. The equilibrium injection-production adjustment has achieved stage results. Compared with the prediction of non adjustment indexes, the average daily oil increase of 1195 sand body after the balanced injection production adjustment is 25m³/D, and the natural decline rate is reduced by 1.1% (Fig. 2).

Figure 1. 1195 sand body production curve
Figure 2. Index prediction of 1195 sand body before and after equilibrium injection-production

4. Conclusion and understanding
According to Buckley Leverett non-piston water drive theory, a production prediction method with variable pressure difference is proposed. In order to achieve the same recovery degree, the method of plane equilibrium injection-production adjustment in unit time is put forward. This method has strong applicability, can be used to adjust the injection-production balance of irregular well pattern, and has the characteristics of convenient calculation. The evaluation coefficient of the optimal equilibrium injection-production scheme is defined, which can guide the optimization of the equilibrium injection-production scheme.

Acknowledgments
This work was financially supported by Bohai oilfield infilling adjustment and EOR reservoir engineering technology demonstration (2016zx05058001), a major national science and technology project of China

References
[1] Wang Delong, Guo Ping, Wang Zhouhua et al. Study on Equilibrium Displacement Effects of Injection-Production Well Group in Heterogeneous Reservoirs [J]. Journal of Southwest Petroleum University(Science & Technology Edition), 2011, 33(5):122-125.
[2] Yan Ke, Zhang Jun, Wang Benzhe et al. Balance Water Flooding of Adjustment of Plane Heterogeneous Reservoirs [J]. Special Oil and Gas Reservoirs, 2015, 22(5):86-89.
[3] Zhu Shengjiu, An Xiaoping, Zhang Jiaosheng. Study on Optimized Injection-Production pressure difference based on breakthrough velocity [J].Petroleum Geology and Engineering, 2016, 30(3):108-110.
[4] Wang Jun. Flow Rate Design for Equilibrium Displacement of Flood Pattern [J]. Special Oil and Gas Reservoirs, 2015, 12(6):37-39.
[5] Zhou Yongxi, Wang Yong, Cheng Yanhu et al. Development Counter Measures Research for Permeability Anisotropy Reservoirs [J]. Journal of Southwest Petroleum Institute, 2005, 27(3):42-45.
[6] Wang Xiang, He Yanfeng, Feng Qihong et al. A Well Pattern Design Method for Heterogeneous Reservoir Based on the Concept of Equilibrium Displisment [J]. Journal of Changzhou University(Natural Science Edition), 2018, 30(6):41-46.
[7] Feng Qihong, Wang Xiang, Wang Duanping et al. Theoretical analysis on the performance of equilibrium displacement in water flooding reservoir [J]. Petroleum Geology and Recovery Efficiency, 2016, 23(3):83-88.
[8] Cui Chuanzhi, Liu Lijun, Feng Ya et al. Layer classification and rational sectional water injection allocation method based on equilibrium displacement [J]. Petroleum Geology and Recovery Efficiency, 2017, 24(7):67-71.
[9] Ma Kuiqian, Chen Cunliang, Liu Yingxian et al. Separate-Layer Water Injection Allocation Based
7

[10] Wang Jijun, Zhou Haiyan, Zhang Chi et al. Research on Vertical Equilibrium Displacement Based on Laying Defining Treshold [J]. Natural gas and oil, 2018, 36(4):54-56.

[11] Sun Zhaobo, Li Yunpeng, Jia Xiaofei et al. A Method to Determine the Layered Injection Allocation Rates for Water Injection Wells in High Water Cut Oilfield Based on Displacement Quantitative Characterization [J]. Petroleum Drilling Techniques, 2018, 46(2):87-91

[12] Zhang Wei, Long Ming, Li Jun et al. A New Method for Determining the Flooding Range of Oil Well in Bottom-Water Reservoir Based on Dynamic Production [J]. Natural gas and oil, 2017, 35(4):68-71.

[13] Wang Ping, Jiang Ruizong, Wang Gongchang et al. Numerical Simulation of Factors Affecting Water-flooding in High Water-cut Stage [J]. Natural gas and oil, 2012, 30(4):36-38. 36(4): 54-56.

[14] Wang Jijun, Zhou Haiyan, Zhang Chi et al. Research on Vertical Equilibrium Displacement Based on Laying Defining Treshold [J]. Natural gas and oil, 2018, 36(4):54-56.

[15] Han Guangming, Dai Zhaoguo, Yang Jianlei et al. Liquid producing capacity optimization method under multiwell interference based on equilibrium displacement [J]. Oil Drilling & Production Technology, 2017, 39(2): 254-257.

[16] Cui Chuanzhi, An Ran, Li Kaikai et al. Waterflooding Injection — Production Pressure Difference Optimization in Low—Permeability Reservoir [J]. Special Oil and Gas Reservoirs, 2016, 23(3): 83-85.

[17] Chang Huijiang, Sun Guangyi, Chen Xiaoming et al. Lateral Injection — Production Optimization and Application Based on Balanced Flooding [J]. Special Oil and Gas Reservoirs, 2019, 26(4): 120-123.